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DEVELOPMENT OF LOW-COST WELDING PROCEDURES FOR THICK SECTIONS OF HY-150 STEEL

By

P. M. Schmidt and R. S. Snow

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA Lewis Research Center

Contract NAS 3-12056

John A. Misencik, Project Manager

GENERAL DYNAMICS
Electric Boat Division

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Final Report

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Cleveland, Ohio
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FOREWORD

This report summarizes work performed by the Electric Boat Division of General Dynamics Corporation from June 1969, to July 1971, under Contract NAS 3-12056. The work was administered under the direction of Mr. John A. Misencik of the NASA Lewis Research Center. Overall responsibility for the contractual performance of General Dynamics was vested in Mr. J. M. Cameron, Manager of Welding and Materials Engineering. Technical responsibility was vested in Mr. J. Lanzafame, Chief of Process Development Engineering through D. R. Smith, Supervisor of Structural Welding Development.

General Dynamics personnel who participated in the work described herein include: P. M. Schmidt, project engineer and principal investigator; C. R. Weaver, welding engineer; and R. S. Snow, materials engineer.

All fracture toughness specimen precracking and testing for this contract was performed by Lehigh University Fritz Laboratory, under the direction of Dr. R. G. Slutter; Drs. P. C. Paris, R. P. Wei, and G. C. Sih, all of Del Research Corporation, Hellerstown, Pennsylvania, were retained as consultants in fracture mechanics.

The information contained in this document is also released as General Dynamics/Electric Boat Division Report PDE-170.

ABSTRACT

Low cost welding procedures were developed for welding 6-inch (15.24cm) thick HY-150 steel to be used in the manufacture of large diameter motor case 'Y' rings and nozzle attachment flanges. An extensive investigation was made of the mechanical and metallurgical properties and fracture toughness of HY-150 base plate and welds made with the manual shielded metal arc process and semi-automatic gas metal arc process in the flat position. Transverse tensiles, all-weld metal tensiles, Charpy V-notch specimens and edge notched bend specimens were tested in the course of the program. In addition metallographic studies and hardness tests were performed on the weld, weld HAZ and base metal. The results of the work performed indicate that both the shielded metal arc and gas metal arc processes are capable of producing consistently sound welds as determined by radiographic and ultrasonic inspection. In addition, the weld metal deposited by each process was found to exhibit a good combination of strength and toughness such that the selection of a rolled and welded procedure for fabricating rocket motor case components would appear to be technically feasible.

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SUMMARY

This program was conducted to develop low-cost welding procedures for welding thick sections of HY-150 steel and to use these procedures to fabricate test weldments in 6-inch (15.24cm) thick base material. Extensive tests were conducted to establish the mechanical, metallurgical and fracture toughness properties of these thick sections. The data from this program will help to establish the suitability of using 6-inch (15.24cm) thick HY-150 steel and a rolled and welded fabrication procedure to produce lower cost large-diameter 'Y' rings and nozzle attachment flanges. The work performed included four tasks, three of which were completed. A base plate material characterization study was conducted to determine the mechanical and metallurgical properties of the base plate material. Welds were made in 6-inch (15.24cm) thick HY-150 using the manual shielded metal arc process and the semi-automatic gas metal arc process. The effect of preheat temperature and interpass temperature on the strength and toughness of welds was determined. In addition the use of high wire feed speeds and welding currents were evaluated for welding with the gas metal arc process to determine their effect on weld quality and to maximize the deposition rate for this process. Edge-notched fracture toughness bend tests were performed on welded specimens made with both welding processes and on un-welded plate material. The results of this program established the suitability of both welding processes for producing 'Y' rings and nozzle attachment flanges in a 6-inch (15.24cm) thick HY-150 material. The semi-automatic gas metal arc procedure

SUMMARY (Continued)

was recommended as optimum for the intended application due to the inherently higher deposition rate afforded by this process and the need for more stringent controls required in handling the 14018 manual shielded metal arc electrode in a production environment.

1.0 INTRODUCTION

The use of machined forgings for large diameter Y-rings and nozzle attachment flanges adds considerably to the cost of solid fuel rocket motor cases. Therefore, a program was undertaken to develop welding techniques for welding 6-inch (15.24cm) thick HY-150 steel in an effort to provide low cost weldments which could be used in place of the more expensive forgings.

One of the primary requirements of the optimum welding procedure developed is that the weldments produced exhibit a minimum yield strength of 140,000 psi (966 MPa) in 6-inch (15.24cm) thick plate with sufficient toughness such that unstable crack propagation at stress levels below yield will not occur in structures fabricated of this material. A manual shielded metal arc (SMA*) electrode, Type 14018 AW coated electrode and a gas metal arc (GMA*) bare wire electrode, Type 140-S, both developed under a Navy sponsored contract for welding 5 Ni-Cr-Mo-V steel were used for making the 6-inch (15.24cm) weldments in this program. Work centered primarily on determining which welding process could provide the required welding characteristics, weld metal soundness and the best combination of strength and toughness at lowest cost.

The work of this contract was divided into four major tasks:

- Task I - Review of Existing Data
- Task II - Material Characterization Study
- Task III - Preliminary Evaluation of Weldments
- Task IV - Optimization of Welding Methods

Work on this program was terminated after completion of Task III efforts.

*As defined by the American Welding Society

2.0 MATERIALS, EQUIPMENT AND TESTING PROCEDURES

2.1 MATERIALS

2.1.1 BASE MATERIAL -- All base material used in this program was basic electric furnace air-melted and vacuum-degassed 5% Ni-Cr-Mo-V (HY-150) steel, produced in general accordance with the requirements of MIL-S-24371. It was melted and converted into 6-inch (15.24cm) thick quenched and tempered base plate by United States Steel Corporation, Homestead Works. The heat number was 5P3947. Since no production heat of HY-150 steel had been rolled into 6-inch (15.24cm) thick base plate prior to the production of the plate material used in this program the attainment of a 140,000 psi (966 MPa) minimum yield strength was not guaranteed.

This material was supplied to the Electric Boat Division as two master plates, each 108" x 102" x 6" (274.3cm x 259.1cm x 15.24cm). The plate numbers were F4602 and F4603.

In order to improve base plate hardenability several modifications were made to the chemical composition specified in MIL-S-24371. The carbon content was increased from 0.12% maximum to a range of 0.09 to 0.13%, and other alloying elements tending to increase hardenability or toughness were required to be within the range specified by MIL-S-24371, but at mid-range levels or higher. The maximum percentage of sulfur was reduced from 0.015%, per MIL-S-24371, to 0.010%. Complete base plate chemical analysis data are presented in Table I.

2.0 2.1 2.1.1 (Continued)

Conversion of ingot into plate material was accomplished by first hot forging the ingot to a 20-inch (50.8-cm) - thick slab. This slab was then cut in half and hot-rolled to a 6-inch (15.24-cm) thickness with approximately a 1:1 cross-rolling-ratio.

The plates were ultrasonically inspected for soundness after rolling and each was found to contain a band of numerous small defects. These bands were each approximately 16-inches (40.6-cm) wide, running down the center of each plate parallel to the long dimension. The shapes and locations of these defect areas are illustrated in Figure 1. The defects contained in these areas are attributed to gas and possibly shrinkage porosity at the center of the ingot. The presence of these defects did not significantly affect the results of this program, however, since test pieces were laid-out and removed from each master plate in such a manner that, with one exception, no defects were located in critical areas. The one exception was a lamination that affected the propagation of the fatigue precrack in fracture toughness specimen PD-2BMK, from plate F4602. Figures 2 and 3 illustrate the lay-out of test pieces within each master plate.

Following ultrasonic inspection each master plate was heat-treated as described in Table II. Plate F4603 had to be reheat-treated several times before acceptable mechanical property test results were obtained.

2.0 2.1 (Continued)

2.1.2 WELDING ELECTRODES -- Two types of welding electrodes were used in this program. McKay Company Type E-14018AW coated electrodes were used for shielded metal arc (SMA) welding while Airco Type 140S bare electrode was used for GMA spray-arc welding. All coated electrode was produced from McKay Heat #422W2201, with all 1/8-inch (0.31cm) electrodes being from Lot #281995, Batch #1672 and all 3/16-inch (0.47cm) electrodes from Lot #291795, Batch #2409. The bare electrode was 0.062-inch (0.15cm) diameter, Airco Heat #1P1338. Chemical analysis data for each type electrode and as-deposited weld metal are shown in Table III.

2.2 EQUIPMENT

2.2.1 WELDING EQUIPMENT -- All welding performed in this program was accomplished using D.C. reverse polarity current, supplied by conventional transformer/rectifier power supplies. A 300-ampere drooping-characteristic power supply was used with the SMA process. For GMA spray-arc welding, a 400-ampere constant-potential power supply was used. All preheating was accomplished by use of electric strip heaters. These strip heaters were automatically turned on and off to maintain proper weldment preheat and interpass temperatures for the 2nd and 3rd sets of GMA spray-arc weldments. When the 1st set of GMA and SMA weldments were produced, weldment temperature was measured throughout welding and the heaters removed from the weldment when it became too warm.

2.0 2.2 (Continued)

2.2.2 INSTRUMENTATION -- Welding currents and arc voltages were measured with calibrated tong meters, ammeter and voltmeter recorders. SMA arc voltages were measured between the jaws of the electrode holder and the work piece. Arc times were measured to the nearest second by an electric clock, which automatically turned on and off with the flow and stoppage of welding current.

2.3 TESTING AND INSPECTION PROCEDURES

2.3.1 MECHANICAL PROPERTY TESTS -- All mechanical property tests conducted in this program were performed in accordance with Federal or ASTM Specifications as follows:

a. Tensile Tests: Tensile tests were in accordance with Federal Test Standard 151, Method 211.1. Specimens tested were either Type R1 or R3 round, reduced section specimens with 0.505-inch (1.28cm) or 0.252-inch (0.64cm) diameters, respectively. Gage lengths were 2-inch (5.08-cm) and 1-inch (2.54-cm), respectively.

b. Charpy V-Notch Impact Tests: Impact specimens were all tested on a calibrated Riehle impact machine in accordance with Federal Test Standard 151, Method 221.1.

c. Hardness Tests: All hardness tests performed were in accordance with Federal Test Standard 151, Method 243.1, Rockwell Hardness Test.

2.0 2.3 (Continued)

2.3.2 FRACTURE TOUGHNESS TESTING -- All fracture toughness tests performed were essentially consistent with the methods described in ASTM Test Method E-399-70T. Tests were conducted on full-thickness single-edge-notched bend specimens subjected to four-point loading. In accordance with the contract requirements for this program, base-plate and Task IV weldment specimen length and width dimensions were twice the dimensions required by ASTM Method E-399-70T in proportion to specimen thickness. Task III weldment specimen length was similarly doubled but the width was reduced to only half the width required by Method E-399-70T. The effect, if any, of increases in specimen length and width would be to enhance test quality; decreasing the width of the Task III weldment specimens, however, would tend to degrade rather than improve test quality.

2.3.3 NONDESTRUCTIVE TESTING AND INSPECTION -- All nondestructive testing and inspection of weldments and base plate were performed as follows:

a. Liquid Penetrant, Magnetic Particle and Radiographic Tests: The inspection techniques and standards of acceptance for these tests were in accordance with Sections 6 and 7 of NAVSHIPS 0900-006-9010, Fabrication, Welding and Inspection of HY-80 Submarine Hulls.

2.0 2.3 2.3.3 (Continued)

b. Ultrasonic Tests: Inspection techniques and standards of acceptance for base plate material soundness were in accordance with MIL-S-24371, with weldments being inspected in accordance with NAVSHIPS 0900-006-3010, Ultrasonic Inspection Procedure and Acceptance Standards for Production and Repair Welds.

3.0 TASKS PERFORMED AND PROCEDURES

3.1 TASK I - REVIEW OF EXISTING DATA

Existing data and information relating to the state-of-the-art of HY-150 weldments were thoroughly reviewed prior to the initiation of work in Tasks II, III or IV of this program. This review included personal contact and discussions with research and development personnel from U. S. Steel Corporation, McKay Company, Air Reduction Company and U. S. Naval Research and Development Centers. The results obtained by the Electric Boat Division from several in-depth investigations of HY-130/150 weldments (1, 2, 3) were also reviewed.

The information thus obtained was then analyzed and utilized in the selection and specification of chemical compositions for both the base plate material and in the selection of weld filler wires used in this program.

The review of existing data and information was continued on a current-awareness basis for the duration of this program.

3.2 TASK II - MATERIAL CHARACTERIZATION STUDY

A base plate material characterization study was conducted to determine the mechanical and metallurgical properties of each of the master plates produced for use in this study.

Sample pieces, designated PD-12BM and PD-13BM located as shown in Figures 2 and 3, were taken from each of the two master plates. These samples were then each tested as follows:

3.0 3.2 (Continued)

One - Standard 0.505-inch (1.28cm) transverse tensile test at plate mid-thickness (to determine T.S., 0.2% Y.S., % elongation and % R.A.)

One - Standard 0.505-inch (1.28cm) longitudinal tensile test at plate mid-thickness (to determine T.S., 0.2% Y.S., % elongation and % R.A.)

One - Special short-transverse 0.252-inch (0.64cm) (through the thickness) tensile test (to determine T.S., 0.2% Y.S., % elongation and % R.A.)

One - Transverse Charpy V-Notch impact energy vs. temperature curve at plate mid-thickness, -300°F to +212°F (-148°C to +100°C)

One - Longitudinal Charpy V-notch impact energy vs. temperature curve, mid-thickness, plate F4602,only, -300°F to +212°F (-148°C to +100°C)

One - Micro and macro examination of plate near-surface and mid-surface areas to determine soundness, cleanliness and austenitic grain size.

A complete chemical analysis was performed and numerous Rockwell "C" surface-to-surface traverse hardness readings were taken. Figure 4 shows the location of four areas within Plate F4602 where hardness traverses were run.

In addition, one edge-notched full-thickness fracture toughness bend test, longitudinal specimen designated PD-2BMK and PD-3BMK, was removed from each master plate as shown in Figures 2 and 3.

Specimen dimensions and other details are shown in Figures 4 through 7. Figure 8 illustrates the manner in which all of the fracture toughness specimens tested in this program were loaded to accomplish precracking and testing. The locations and orientations of the tensile and Charpy specimens within pieces PD-12BM and PD-13BM are shown in Figure 9.

3.3 TASK III - PRELIMINARY EVALUATION OF WELDMENTS

The development of welding procedures for shielded-metal-arc (SMA) and spray-gas-metal-arc (GMA) welding HY-150 steel and the selection of an optimum process and procedure for use in Task IV were major objectives of this program. This was accomplished by the production and testing of four (4) sets of two (2) 6" x 6" x 24" (15.24cm x 15.24cm x 60.96cm) and one (1) 6" x 6" x 48" (15.24cm x 15.24cm x 122.2cm) test weldments, with each set being welded with a different welding process or different set of parameters from that used to produce any of the other welds. The selection of parameters to be used in producing these initial weldments was based on the results of the review of existing data (Task I), prior Electric Boat division experience in producing HY-150 weldments and the production and testing of two (2) preliminary weld wire evaluation test plates. The two test plates, weldments PD-4836 and PD-4837, were produced to verify weld wire quality and establish basic strength levels for each wire when deposited under known conditions. These plates were also used as a means of verifying that the welding operators selected to weld subsequent Task III weldments were qualified to do so.

Production of Preliminary Evaluation Test Plates

Weldments PD-4836 and PD-4837 were produced using the parameters and welding conditions listed in Tables IV and V. PD-4836 was welded using the SMA welding process and PD-4837 was GMA spray-arc welded, following the deposition of two SMA root weld beads to close the weld root opening. HY-80 base plate was used for each of these weldments. Restraint was maximized by welding the outside edges of each test plate to a second, larger plate.

Following completion of each weldment and after a seven-day waiting period, each weldment was magnetic particle, liquid penetrant, x-ray and ultrasonically inspected. They were then destructively tested as follows:

3.0 3.3 (Continued)

PD-4836:

Four	- Standard 0.505-inch (1.28-cm) longitudinal all-weld-metal tensile specimens
Twelve	- Standard Charpy V-notch impact test specimens, tested at 0°F, 32°F and 72°F (-17°C, 0°C, and 22°C)
One	- Macro examination

PD-4837:

Eight	- Standard 0.505-inch (1.28-cm) longitudinal all-weld-metal tensile specimens
Twenty-four	- Standard Charpy V-notch impact test specimens, tested at 0°F, 32°F and 72°F (-17°C, 0°C and 22°C)
One	- Macro examination

Specimen locations for each of these weldments are shown in Figures 10 and 11.

Production of 6" x 6" (15.24-cm x 15.24-cm) Weldments

Following an analysis of the results from tests of weldments PD-4836 and PD-4837, parameters were selected for use in producing the first two sets of 6-inch (15.24-cm) wide x 6-inch (15.24-cm) thick weldments. The first set was welded using the SMA process; GMA spray-arc welding was used for the second test. These sets consisted of the following weldments:

3.0 3.3 (Continued)

1st Set (SMA-1)

Weldment PD-4825, 6" x 6" x 48" (15.24-cm x 15.24-cm x 122.0-cm)

Weldment PD-4827, 6" x 6" x 48" (15.24-cm x 15.24-cm x 122.0-cm)

Weldment PD-4826, 6" x 6" x 108" (15.24-cm x 15.24-cm x 274.3-cm)

2nd Set (GMA-1)

Weldment PD-4830, 6" x 6" x 48" (15.24-cm x 15.24-cm x 122.0-cm)

Weldment PD-4831, 6" x 6" x 48" (15.24-cm x 15.24-cm x 122.0-cm)

Weldment PD-4931, 6" x 6" x 108" (15.24-cm x 15.24-cm x 274.3-cm)

The parameters and conditions under which these first two sets of 6" x 6" (15.24-cm x 15.24-cm) weldments were produced are summarized in Tables VI and VII. 3-inch (7.62-cm) run-on/run-off tabs were added to the end of each weld joint to minimize the influence of weld starts and stops on weld mechanical properties and quality.

Following the completion of welding and after a seven-day or longer waiting period had been observed, each weldment was magnetic particle, liquid penetrant, x-ray and ultrasonically inspected. The weldments were then destructively tested as follows:

3.0 3.3 (Continued)

1st Set (SMA-1)

Weldment PD-4825:

Five - Standard 0.505-inch (1.28-cm) longitudinal all-weld-metal tensile specimens

Seven - Standard Charpy V-notch impact specimens, transverse to weld and notched in weld HAZ, tested at 0°F and 72°F (-17°C and 22°C)

Weldment PD-4827:

Six - Standard 0.505-inch (1.28-cm) tensile specimens, transverse to weld with weld HAZ contained in specimen reduced section area

Seven - Standard Charpy V-notch longitudinal all-weld-metal impact specimens, tested at 0°F and 72°F (-17°C and 22°C)

One - Rockwell "C" hardness traverse, across weld into base metal, various levels top-to-bottom

One - Macro examination for soundness and penetration characteristics

Weldment PD-4826:

One - Edge-notched fracture toughness bend specimen, notched in weld

3.0 3.3 (Continued)

<u>2nd Set (GMA-1)</u>

Weldment PD-4830:

Five - Standard 0.505-inch (1.28-cm) longitudinal all-weld-metal tensile specimens

Seven - Standard Charpy V-notch impact specimens, transverse to weld and notched in weld HAZ, tested at 0°F and 72°F (-17°C and 22°C)

Weldment PD-4831:

Six - Standard 0.505-inch (1.28-cm) tensile specimens, transverse to weld with weld HAZ contained in specimen reduced section area

Seven - Standard Charpy V-notch longitudinal all-weld-metal impact specimens, tested at 0°F and 72°F (-17°C and 22°C)

One - Rockwell "C" hardness traverse, across weld and into base metal, various levels top-to-bottom

One - Macro examination for soundness and penetration characteristics

Weldment PD-4931

One - Edge-notched fracture toughness bend specimen, notched in weld

3.0 3.3 (Continued)

Specimen locations and orientations for each of these weldments are shown in Figures 12 and 13. Fracture toughness bend specimens are shown in Figure 14. Specimen loading during precracking and testing was as shown in Figure 8.

Upon the completion of testing of these first two sets of weldments parameters for the third and fourth sets were selected. These last two sets consisted of the following weldments:

3rd Set (GMA-2)

Weldment PD-4824, 6" x 6" x 48" (15.24-cm x 15.24-cm x 122.0-cm)

Weldment PD-4828, 6" x 6" x 48" (15.24-cm x 15.24-cm x 122.0-cm)

Weldment PD-4829, 6" x 6" x 108" (15.24-cm x 15.24-cm x 274.3 cm)

4th Set (GMA-3)

Weldment PD-4833, 6" x 6" x 48" (15.24-cm x 15.24-cm x 122.0-cm)

Weldment PD-4834, 6" x 6" x 48" (15.24-cm x 15.24-cm x 122.0-cm)

Weldment PD-4835, 6" x 6" x 108" (15.24-cm x 15.24-cm x 274.3 -cm)

The parameters selected are summarized in Tables VIII and IX. Both of these sets were welded using the GMA spray-arc welding process.

The major differences between each of these latter two sets of weldments and set GMA-1 were interpass temperature, welding heat input energy and welding current.

3.0 3.3 (Continued)

Set GMA-1 was welded with a constant welding current and constant heat input energy with variations in interpass temperature. These variations were the result of using temperature-sensitive crayons to measure interpass temperature and taking temperature readings near (rather than right on) the point where a weld bead was to be subsequently deposited. This is usually the manner in which such crayons are used in order to avoid crayon material contaminating the weld. This method was found inadequate to control interpass temperature for 6-inch (15.24cm) HY-150 weldments.

The interpass temperature of the third set of weldments (GMA-2) was therefore measured with a contact pyrometer, with temperature measurements being taken right at the point where the next weld bead was to be deposited. This resulted in a much better control of weld interpass temperature. In addition to this change, set GMA-2 was welded with several combinations of welding interpass temperature and heat input energy, each of which was expected to result in equivalent weld metal cooling rates[3] and therefore equal weld metal yield strengths of approximately 140 Ksi (966 MPa).

The fourth set of weldments was produced using two different levels of welding heat input energy and essentially a fixed low interpass temperature. Initial welding was performed using a high heat input energy, selected to determine if the combination of a low interpass temperature and high heat input energy would result in hydrogen cracking or hydrogen embrittlement problems. A low heat input energy was used, however, to weld the outer, near-surface areas of this set of weldments. This combination of parameters was used in an attempt to attain a high weld metal yield strength from specimens taken from these areas. No previously used combination had consistently provided high i.e., 140 KSI (966 MPa), weld metal yield strengths in these areas.

Upon completion of welding, and after a seven-day or longer waiting period had elapsed, each of these weldments was magnetic particle, liquid penetrant, x-ray and ultrasonically inspected. The weldments were then destructively tested as follows:

3rd Set (GMA-2)

Weldment PD-4824:

- Six - Standard 0.505-inch (1.28-cm) tensile specimens, transverse to weld with weld HAZ contained in specimen reduced section area

- Seven - Standard Charpy V-notch longitudinal all-weld-metal impact specimens, tested at 0°F and 72°F (-17°C and 22°C)

- One - Rockwell "C" hardness test, with traverses across weld, along HAZ and into base metal, at various levels top-to-bottom.

- One - Macro examination for soundness and penetration characteristics

3.0 3.3 (Continued)

Weldment PD-4824 (Continued):

Two - Chemical analyses of as-deposited weld metal, from broken tensile specimens

Weldment PD-4828:

Five - Standard 0.505-inch (1.28cm) longitudinal all-weld-metal tensile specimens

Three - Standard 0.252-inch (0.64cm) longitudinal all-weld-metal tensile specimens

Seven - Standard Charpy V-notch impact specimens, transverse to weld and notched in weld HAZ, tested at 0°F and 72°F (-17°C and 22°C)

Weldment PD-4829:

One - Edge-notched fracture toughness bend specimen, notched in weld

<u>4th Set (GMA-3)</u>

Weldment PD-4833:

Five - Standard 0.505-inch (1.28cm) longitudinal all-weld-metal tensile specimens

Seven - Standard Charpy V-notch impact specimens, transverse to weld and notched in weld HAZ, tested at 0°F and 72°F (-17°C and 22°C)

One - Rockwell "C" hardness test, with traverses across weld or various levels, surface-to-surface

3.0 3.3 (Continued)

Weldment PD-4833 (Continued):

One - Macro examination for soundness and penetration characteristics

Weldment PD-4834:

Five - Standard 0.505-inch (1.28cm) tensile specimens transverse to weld with weld HAZ contained in specimen reduced section area

Seven - Standard Charpy V-notch impact specimens, transverse to weld and notched in weld HAZ, tested at 0°F and 72°F (-17°C and 22°C)

One - Macro examination for soundness and penetration characteristics

One - Rockwell "C" hardness test, with traverses across weld at various levels, surface-to-surface

Weldment PD-4835:

One - Edge-notched fracture toughness bend specimen, notched in weld

After testing of these last two sets of weldments was completed, all Task III test data was analyzed and an optimum low-cost HY-150 welding procedure was selected for use and evaluation in Task IV of this program.

3.0 (Continued)

3.4 TASK IV - OPTIMIZATION OF WELDING METHODS

This program was terminated after all Phase III work was successfully completed.

4.0 RESULTS AND DISCUSSION

4.1 TASK I

The results of Task I indicated the attainment of a 140,000 psi (966 MPa) minimum yield strength in 6-inch (15.24cm) thick HY-150 plate would require slight modifications to the chemical composition specified in MIL-S-24371, accurate control of plate chemical composition and an accelerated quench from the austenitizing temperature. An increase appeared to be necessary in plate carbon content, from the normally specified 0.12% maximum to 0.13% maximum. In addition, it appeared necessary to maintain all other elements tending to increase hardenability or toughness at mid-range levels or higher, and to limit the amount of sulfur to a maximum of 0.010%. All of these changes were incorporated into the chemical composition requirements specified when the HY-150 base plate used in this program was ordered.

The review of available information relating to SMA or GMA welding HY-150 steel indicated several potential problem areas. First, only one SMA welding electrode manufacturer, the McKay Company, had been successful in developing an electrode which had the capability to provide 140,000 psi (966 MPa) minimum yield strengths with 50 ft.-lbs. (68 joules) or greater impact energy at 72°F (22°C).

Second, the operability of this electrode was not well proven.

4.0 4.1 (Continued)

A third, and more important problem was that this electrode had not been used to weld heavy section plate material or joints that were under high restraint. This was a cause for concern because one of the major problems in SMA welding HY-150 steel is hydrogen-induced cold cracking.[4] This cracking typically occurs a considerable time, hours and sometimes days, after a weld has been completed and allowed to cool. Under otherwise equal conditions, such cracking is most likely to occur when a weldment is highly restrained or where thick sections are being welded. Water, in the form of moisture in SMA welding electrode coatings, can cause such cracking problems. Specification MI-30CE/1, invoked on the SMA welding electrodes purchased for use in this program, restricts the maximum moisture content to 0.10%, by weight. This is less than the 0.20% more commonly specified for SMA electrodes used to weld other quenched and tempered steels, such as HY-80.

A fourth area of concern was that limited data from tests conducted by the Electric Boat division[2] have indicated hydrogen embrittlement can occur under certain conditions in HY-150 weldments using the spray-arc GMA welding process.

4.0 (Continued)

4.2 TASK II

The results of U. S. Steel and E. B. division chemical analyses of the two base plates produced for use in this program are given in Table I. Each of these plates can be seen to have met the specified chemical composition requirements, except that the phosphorous content was 0.001-0.002% high on check analysis. Base plate tensile properties are summarized in Table X, and Charpy V-notch impact test results are shown in Tables XI and XII. CVN impact energy vs. temperature curves for specimens from each master plate are shown in Figures 15 and 16. Impact energy begins to drop at temperatures below approximately 72°F (22°C). At -200°F (-128°C), CVN impact energy had dropped to approximately 20 ft.-lbs. (27 joules).

Yield strengths for these plates were reported by U. S. Steel as ranging from 138,620 to 144,540 psi (956 MPa to 997 MPa) for plate F4602 and from 139,870 to 140,470 psi (965 MPa to 969 MPa) for plate F4603, for specimens tested transverse to the major direction of rolling and taken at the plate mid-thickness. These specimens were taken from excess material at each end of each plate, prior to trimming the plates to final size. Similar tests performed by the Electric Boat division using specimens taken from pieces PD-12BM (plate F4602) and PD-13BM (plate F4603) indicated transverse mid-thickness yield strengths of 135,500 psi

(935 MPa) and 139,000 psi (959 MPa). The goal of a 140,000 psi (966 MPa) minimum 0.2% offset yield strength was thus not attained. It is felt, however, that such a yield strength level could have been attained if a slightly more severe quench could have been applied to these plates after austenitizing.

Tables XI and XII summarize the results of U. S. Steel and Electric Boat division Charpy V-notch (CVN) impact tests of transverse and longitudinal specimens taken from mid-thickness areas of each plate and tested at various temperatures. CVN impact temperature transition curves are shown in Figures 15 and 16. MIL-S-24371 requires the average of such transverse specimens to be not less that 60 ft.-lbs. (81.6 joules) at each of two temperatures, 70°F (21°C) and 0°F (-17°C). Average test results reported by U. S. Steel were 52 ft.-lbs. (70.5 joules) at 72°F (22°C) and 50 ft.-lbs. (68 joules) at 0°F (-17°C) for plate F4602 and 62 ft.-lbs. (84.4 joules) at 72°F (22°C) and 54 ft.-lbs. (73.4 joules) at 0°F (-17°C) for plate F4603. Test results reported for other specimens which were similar but tested longitudinal to the major direction of rolling were 61 and 58 ft.-lbs. (83 and 79 joules) at 72°F (22°C) and 0°F (-17°C), respectively for plate F4602. For plate F4603, 72°F (22°C) and 0°F (-17°C) values were 71 and 59 ft.-lbs. (96.5 and 80.2 joules), respectively.

4.0 4.2 (Continued)

Tests performed by the Electric Boat division showed transverse specimen impact values of 62 and 44 ft.-lbs. (84.3 and 59.8 joules) at 76°F (24°C) and 0°F (-17°C), respectively, for plate F4602. Plate F4603 was tested only for transverse direction impact properties. Test results were 65 and 52 ft.-lbs. (88.5 and 70.7 joules) at 76°F (24.4°C) and 0°F (-17°C), respectively.

The fact that plate F4603 exhibited mid-thickness impact properties which were superior to those of plate F4602 while also exhibiting higher yield strengths could be an indication that the mid-thickness region of plate F4602 was quenched less severely and consisted of a more baintic structure than the mid-thickness region of plate F4603. At equivalent strengths, bainite is typically less tough than tempered martensite. In addition, plate F4603 was swung lengthwise in the quench tank during mill heat treating, and appeared to have been more severely quenched than plate F4602, which was lowered into the quench tank and bounced slightly but otherwise not moved while submerged. A less severe quench would be more likely to result in the formation of bainite in mid-thickness regions of such heavy plates.

Photomicrographs of samples from near-surface and mid-thickness areas of plate F4602 are shown in Figure 17. A greater amount of bainite can be seen in the photomicrograph of the mid-thickness area.

4.0 4.2 (Continued)

The results of hardness traverses made with a Rockwell hardness tester parallel to the plate surfaces at five locations through the thickness, i.e., near the top and bottom surfaces, at the plate mid-thickness and half-way between the mid-thickness and each outer surface - indicate no significant difference in hardness through the thickness of plate F4602. One set of such hardness traverses was made on the base metal of each of four weldments, PD-4824, PD-4827, PD-4831 and PD-4834. All of these pieces of base metal came from plate F4602 and were located as previously shown in Figure 4.

A maximum difference in hardness of 5.2 points Rockwell "C" was observed between the top and bottom surfaces of base plate in specimen PD-4834. Specimens PD-4824 and PD-4827 had nearly the same hardness on each surface, and specimen PD-4831 exhibited a difference of only 2.5 points Rockwell "C". The maximum variation in hardness through the thickness of any specimen other than PD-4834 was 2.5 points Rockwell "C". Average hardness readings taken through the thickness for each of these four specimens are summarized below:

HARDNESS VARIATIONS THROUGH THICKNESS

	PD4824	PD4827	PD4831	PD4834
Top	34.7	36.5	33.8	35.9
Top Center	35.2	35.7	34.8	35.7
Center	33.3	34.8	33.8	36.7
Bottom Center	33.1	34.1	35.4	37.9
Bottom	35.2	35.9	36.3	40.9

In this study of base metal hardness, only those points well removed from the weld and heat-affected-zones were used. Readings from at least six points of each traverse were used in calculating each of the average hardness values shown. Additional information and data on base metal hardness test results are presented and discussed in relation to weldment hardness test results in Section 4.3 .

Initial attempts to determine an austenitic grain size for the HY-150 base plate used in this program were unsuccessful. The carburizing method outlined in ASTM Method E-112 for low carbon alloy steel did not reveal the austenitic grain boundaries. At the suggestion of a U. S. Steel metallurgist, the carburized specimen was heated to 900°F-925°F (482°C-496°C), held for 12 hours at this temperature and then water quenched. After a surface of the specimen was polished, it was etched in an aqueous solution of picric acid and sodium tridecylbenzene sulfonate. The prior austenite grains were delineated, but were so fine that resolution could be obtained only at 400X, and only the grain boundaries within the carburized surface zone were revealed by this technique. The "Q" correction factor, described in Note 2 of E-112 was used to convert the grain size measured at 400X to the estimated ASTM size #10.5, which is in terms of measurement at 100X. Average diameter of the grains is 0.00944 mm, per Table 2 of Method E-112.

4.0 4.2 (Continued)

The large size and high-load requirements of the base metal fracture toughness test specimens made it preferable to fatigue-precrack and test them at the Fritz Engineering Laboratory of Lehigh University, Bethlehem, Pa., where sufficiently large testing equipment was available.

Precracking of the specimens at the root of the notch was accomplished with the specimen mounted in a testing frame as a cantilever beam, shown in Figure 18. A hydraulic piston attached between the test frame and the free end of the specimen provided a controllable cyclic force.

The fatigue precrack contained in specimen PD-3BMK initiated at 32,000 cycles, and was completed at 352,000 cycles. The crack was extended about 2-inches (5.08cm) in depth. The maximum stress intensity factor K_{fI} at crack initiation was 59.2 Ksi $\sqrt{in.}$ (65.1 MPa·m 1/2), and ΔK_{fI}, the stress intensity range, was 54.3 Ksi $\sqrt{in.}$ (59.7 MPa · m 1/2). The maximum stress intensity factor at completion of the crack, K_{fF} was 44.3 Ksi $\sqrt{in.}$ (48.8 MPa · m 1/2), and the stress intensity range ΔK_{fF} was 37.7 Ksi $\sqrt{in.}$ (41.5 MPa · m 1/2).

For specimen PD-2BMK, the precrack initiated at 60,000 cycles and was completed by 577,600 cycles. Maximum stress intensity factor at crack initiation was 63.2 Ksi $\sqrt{in.}$ (69.5 MPa · m 1/2) and ΔK_{fI} was 58.1 Ksi $\sqrt{in.}$ (64 MPa · m 1/2). The maximum stress intensity factor at completion of the precrack was 43.6 Ksi $\sqrt{in.}$ (48 MPa · m 1/2), and ΔK_f at completion was 39.5 Ksi $\sqrt{in.}$ (43.4 MPa · m 1/2).

4.0 4.2 (Continued)

The precrack in specimen PD-3BMK was somewhat elliptical in shape but did meet the criteria for uniformity specified in Para. 7.2.3 of ASTM Method E-399. The precrack in specimen PD-2BMK failed to meet the requirements for uniformity. A double-lobed precrack developed because of a lamination at about 1/4 thickness through the plate, and the precrack did not extend to the surface of the specimen on one side. Pre-crack shapes and dimensional details for these specimens are shown in Figures 19 and 20.

Both specimens exhibited mixed-mode fracture in the toughness test. For each specimen a large plastic zone developed ahead of the fatigue crack, and shear lips, each one about one-fifth of the specimen thickness, formed at the specimen surfaces as shown in Figure 21.

Stress intensity factors, K_Q, were calculated using the loads at the intersection of the 5% secant offset line with the load vs. crack-opening-displacement curve, which was obtained autographically during the rising load fracture tests. Calculated values were 270 Ksi $\sqrt{\text{in.}}$ (297 MPa$\cdot$m 1/2) for specimen PD-3BMK and 214.5 Ksi $\sqrt{\text{in.}}$ (236.2 MPa$\cdot$m 1/2) for PD-2BMK. In order for these values to be considered as valid K_{IC} determinations in accordance with ASTM Method E-399, the following condition must be satisfied:

4.0 4.2 (Continued)

$$b = 2.5\left[\frac{K_{IC\ Max.}}{\sigma_{y.s.}}\right]^2$$

or, as rearranged $K_{Max.} = \sigma_{y.s.}\sqrt{\frac{b}{2.5}}$

Where: b = Specimen thickness, inches (cm)

K = Stress intensity factor measured, psi $\sqrt{in.}$ (MPa • m 1/2)

$\sigma_{y.s.}$ = Material yield strength, psi (MPa)

The maximum K_Q values which can be measured by specimen PD-2BMK and PD-3BMK and yet be valid K_{IC} determinations are therefore:

$$K_{Max.}, \text{ PD-2BMK} = 133.5\sqrt{\frac{6}{2.5}} = 207 \text{ Ksi } \sqrt{in.} \ (228 \text{ MPa} \cdot \text{m } 1/2)$$

$$K_{Max.}, \text{ PD-3BMK} = 140.0\sqrt{\frac{6}{2.5}} = 217 \text{ Ksi } \sqrt{in.} \ (239 \text{ MPa} \cdot \text{m } 1/2)$$

Neither specimen appear to meet the requirements of ASTM E-399 for a valid K_{IC} determination. In addition, specimen PD-2BMK does not meet the ASTM criteria because of the poorly formed fatigue crack front. The fracture toughness values should be considered only as engineering toughness values, therefore, and not as critical stress intensity (K_{IC}) values.

A summary of base metal fracture toughness test data is presented in Table XIII.

The load-displacement diagrams shown in Figures 22 and 23 for each of the two base metal fracture toughness tests were similar to the Type I curve shown in Figure 8 of ASTM E-399, except that final fracture of the specimens occurred well after the maximum load had been attained, and considerable plastic deformation of the metal was accompanying extension of the crack.

When a material fails by plastic instability in a fracture test, the data obtained can be used in engineering design if the data is presented as a curve of resistance to crack extension vs. effective crack depth. This data plot is commonly known as an "R-Curve". By the use of an R-curve, the stress required to cause a crack of given depth in a structure to propagate plastically in an unstable manner (essentially, to cause failure of the structure) can be determined.

R-curves for these two base plate K_{IC} toughness specimens and four Task III weldment specimens have been plotted in Figure 24. Critical effective crack depths (crack plus plastic zone radius) have been determined and plotted in each case for an applied stress equal to the nominal yield strength of the material, 140 Ksi (966 MPa).

4.0 4.2 (Continued)

These curves were constructed by the substitution of numerical values obtained from specimen fracture toughness tests into the following equation:

$$R = \frac{PL}{BW3/2} \quad f(a/w)^{1/2}$$

Where:

R = The crack extension resistance, Ksi $\sqrt{in.}$ (MPa·m 1/2)

P = Load in lbs.

L = Distance between inner and outer load points in 4-point loading, inches (cm)

B = Thickness of specimen, inches (cm)

W = Width of specimen, inches (cm)

The effective crack depth "a" was derived from examination of the test record. The crack extention resistance curve is a plot of the computed "R" vs. the effective crack depth. The mechanics of deriving "a" from the test data have been explained by Vazquez and Paris.[5]

The critical crack depth for any applied stress can be determined by constructing the curve of crack extension resistance vs. effective crack depth for the applied stress of interest so that it is tangent to the material response curve.

The equation for the constant stress curve is:

$$\sigma = R/y \sqrt{a}$$

Where:

R = The crack-extension resistance, Ksi $\sqrt{in}$ (MPa·m 1/2)

a = Crack depth, inches (cm)

y = Function of specimen geometry and crack depth to specimen width (a/w) ratio.

Numerical values have been computed for "y" for various "a/w" ratios and the several common configurations of fracture toughness specimens. These values have been plotted in "K" calibration curves.[5]

The point of tangency denotes the critical crack depth. At less than the critical crack depth, the resistance to crack extention of the material is greater than the energy available to extend the crack in a structure under load. At the critical point, the crack extending-force equals the material resistance to crack extension. At a depth greater than critical, there is sufficient energy to overcome the resistance to crack growth, and the crack extends to the limit of the structure, unless the load is removed. Since the energy consumption is high, due to large plastic straining, the crack does not run at the velocities encountered in plane strain (brittle) fracture.

Dissertations on material response curves are given in the aforementioned paper by Vazquez and Paris,[5] and also by Srawley and Brown.[6]

4.3 TASK III

Preliminary Weldments

Weldment PD-4837 is shown partially completed in Figure 25. The weldment can be seen to be edge fillet welded to the welding table top to assure minimum transverse or angular shrinkage and maximum weldment restraint. This was desirable since one of the reasons for producing these weldments was to determine whether hydrogen cracking problems could be encountered when welds were made under high restraint using the electrodes purchased for use in this program. When weldment PD-4836 was welded it was similarly put under high restraint.

The results of nondestructive tests of these weldments did not reveal any rejectable defects. No defects were detected by radiography and only two small indications, acceptable per NAVSHIPS 0900-006-3010, were detected in each weldment during ultrasonic testing. 10X macro-examinations of these weldments revealed no visible defects. Photographs of each of the two macro sections examined are shown in Figure 26. Results of destructive tests are summarized in Tables XIV through XVI. The following observations or conclusions were made based on the results of these nondestructive and destructive tests:

a. The weldors, i.e.- welding equipment operators, who produced these weldments were capable and qualified to weld HY-150 steel using the particular processes employed.

b. The SMA and GMA electrodes purchased for use in this program were not prone to hydrogen cracking under the conditions employed to produce these test weldments. These conditions, however, were not as severe as those which would be encountered in subsequent Task IV weldments. Thus, although it had been demonstrated that

4.0 4.3 b. (Continued)

the electrodes were resistant to hydrogen cracking under high restraint, it had not been definitely established that hydrogen cracking would not be encountered when subsequent Task III and IV weldments were produced.

c. The electrodes purchased for use in this program were capable of producing welds of 140,000 psi (966 MPa) minimum yield strength and 50 ft.-lbs. (68 Joules) minimum Charpy V-notch impact energy at 72°F (22°C).

d. Use of the compound-angle weld joint design originally proposed for Task III and Task IV weldments did not appear to be necessary. The 45° included angle double-vee weld prep used in producing the two preliminary weld wire evaluation weldments was found adequate and more economical. Both of these weld joint designs are shown in Figure 28.

e. For each weldment, the initial side welded appeared to exhibit slightly higher strength and lower impact energy than the second side. Based on the results from only these two weldments it was not possible to establish whether this was actually happening or if other variables, such as variations in weld bead size and/or welding heat input energies were actually the cause.

4.0 4.3 (Continued)

f. All-weld-metal tensile and Charpy specimens indicated a loss in yield strength and an increase in impact energy for weld metal deposited in outer, near-surface areas of the weld. Again, based on only these two weldments a conclusive determination could not be made as to the cause of these differences.

Based on the preceeding observations and conclusions and the results of Task I, parameters were selected for use in producing the first two sets of 6-inch x 6-inch (15.24cm x 15.24cm) weldments.

<u>1st Set (SMA-1)</u>

The parameters previously shown in Table VI were selected for use in producing this set of weldments on the basis of several considerations. The welding current and arc voltage were selected for maximum operability based on experience gained from producing weldment PD-4836. Although the 200°F (93°C) preheat temperature used in producing PD-4836 had appeared adequate for that particular weldment, a higher preheat was felt necessary for these 6-inch (15.24cm) thick weldments. Both the increase in weldment thickness and the fact that the base plate was HY-150 instead of HY-80 would increase the amount of restraint imposed on the weld metal of these weldments. A 250°F (121°C) preheat was, therefore, selected.

Interpass temperature was intended to range between 250°F (121°C) and 275°F (135°C), with Tempil sticks being used to check weldment temperatures at various points within approximately 2-inches (5.08 cm) of, but not on, previously deposited weld metal or the weld-prep surfaces prior to the deposition of each layer of weld beads. This method of measurement, although adequate for weldments of up to approximately a 2-inch (5.08 cm) thickness, was found inadequate for 6-inch (15.24cm) thick weldments. Measurements of weldment temperatures taken near the completion of the second set of weldments, i.e., weldments PD-4830, PD-4831 and PD-4931, indicated a contact pyrometer should be used to measure preheat temperature prior to the deposition of each weld bead, directly on the surface over which the bead would be deposited.

The use of a higher preheat temperature for this first set of 6" x 6" (15.24cm x 15.24cm) weldments was felt to require the use of a lower weld heat input energy if no loss of weld yield strength was to result. Consequently, weld heat input energy was typically limited to a maximum of 30,000 joules/in. (11,800 joules/cm), compared to 35,000 joules/inch (13,800 joules/cm) for weldment PD-4836. Some initial weld beads were made using heat input energies of approximately 47,000 joules/inch (18,500 joules/cm). These beads were intended for testing and comparison with outer, low heat input areas.

No special effort was made to control weld joint geometry accurately or to obtain good weld joint fit up when these weldments were produced. The mismatch shown in Figure 30 is typical of all weldments produced in this program. In some instances, mismatch was worse than shown in this figure.

Results of nondestructive tests of these weldments indicated one rejectable defect was contained in PD-4826. This defect was detected by ultrasonic inspection but not by radiographic or M.P. inspection. Based on U.T. results, it was approximately 2-inches (5.08cm) long and equivalent to approximately a 3/64-inch (0.11cm) or larger diameter cylinder. It was not observed, however, in the fracture surfaces exposed after the weldment was broken in half during fracture toughness testing. Ultrasonic inspection also detected two small, acceptable, indications in weldment PD-4825. No. U.T. indications were observed during testing of PD-4827.

The results of mechanical property tests performed on this set of weldments are summarized in Tables XVII and XVIII. Welding heat input energy data for the weld beads contained in those areas from which tensile specimens were taken are summarized in Table XIX.

These data indicate that the yield strength of longitudinal all-weld-metal specimens taken from these weldments varied from a low 134.5 Ksi (928 MPa) for specimens taken from outer, near surface areas to a high of 143.0 Ksi (987 MPa) for specimens taken from the mid-thickness area. This difference is considered due principally to the differing preheat temperatures which were used in completing these weldments. Where higher preheat temperatures were employed, weld metal yield strength decreased. In the case of the mid-thickness specimen PD-4825-T3 a second factor, weld metal dilution, is also considered to have been significant. The carbon content of typical as-deposited weld metal was between 0.08 and 0.09 percent, while that of the base plate was 0.10 to 0.11 percent. Carbon strongly affects the strength of HY-150 weld metal and enough dilution was probably occurring in mid-thickness weld beads to increase yield and tensile strengths.

The transverse tensile test specimens, which include areas of weld metal, heat-affected-zone and base metal in the reduced section areas all broke in the weld metal. The strengths co-related quite well with the strengths indicated by the longitudinal all-weld-metal tensile specimens taken from corresponding weld areas.

As shown in Table XVIII, Charpy V-notch impact energies obtained from specimens taken from these weldments were outstanding. The average 72°F (22°C) impact energy from specimens notched in the weld HAZ was 75 ft.-lbs. (102 joules) and 63 ft.-lbs. (85.7 joules) at 0°F (-17°C). The average all-weld-metal impact energy at 72°F (22°C) was considerably higher - 98 ft.-lbs. (133 joules) - and 91 ft.-lbs. (124 joules) at 0°F (-17°C). These values are quite impressive considering the relatively high strength of this material and that they were obtained from weld metal deposited using the SMA process.

A photomacrograph through PD-4827 is shown in Figure 29. A hardness traverse pattern is shown in Figure 30; with Rc hardness values for the various test points summarized in Table XX.

The engineering fracture toughness, K_Q, of weldment PD-4826 was difficult to establish because of precrack shape irregularities and the fact that the 5% secant offset method recommended in ASTM Method E-399-70T is quite conservative. Two different approaches were followed. The first of these was based on the use of a 5% secant offset load as recommended in the ASTM Method and an assumed crack depth equal to the maximum actual crack depth measured after fracture. Using this approach, K_Q was estimated as 194 Ksi $\sqrt{\text{in.}}$ (214 MPa $\cdot$ m 1/2). This value is, as previously indicated, quite conservative. It is based on a method of testing which is intended to somewhat under-rate the toughness of a material. It is not necessarily the closest estimate of the useful engineering toughness of the material. These values are recommended, however, as a basis for engineering or design calculations. Paris recommended a somewhat different approach which is believed to more accurately measure the K_Q engineering fracture toughness. This approach was based on the use of compliance calibrations determined by Gross, Roberts and Srawley of NASA Lewis Research Center[7]. A secant line was drawn from the maximum load point in the load-displacement record to the origin and an effective crack size was computed using the compliance calibrations. This effective crack size and the maximum load were then used in computing a K_Q value from the usual formula for the specimen. The value of K_Q determined by this crack size by compliance method was 287 Ksi $\sqrt{\text{in.}}$ (316 MPa · m 1/2), indicating outstanding toughness. The fracture surface and shape of the precracked area of specimen PD-4826 is shown in Figure 31, along with pertinent dimensional data. The load displacement record of this specimen is shown in Figure 32.

The same phenomonon of fatigue pre-crack irregularity exhibited by the HY-150 welded specimens was also encountered in previous fracture toughness testing of 12% nickel-maraging steel weldments.[8] The problem has been reported[9] to be with residual welding stresses, which are tensile in direction near the surface of the weld, and compressive at the center of the weld. Under tensile loading in Mode I, for fatigue crack development, load stresses and residual stresses at the weld surface are additive in a tensile direction, which encourages crack initiation. At the weld center, the tensile stress due to load may not overcome the compressive residual stress; or if it does, may induce only weak tensile stress, below the endurance limit. Hence fatigue cracking is confined to the areas of residual tensile stress. Thermal stress relief, or mechanical working can be used to reduce or re-distribute residual stress and improve the probability for generating a straight fatigue crack front. Such processing may, however, affect the fracture toughness characteristics of the weld as it will be used in service.

2nd Set (GMA-1)

This set of weldments was produced using the conditions and parameters previously shown in Table VII. As in the case of the first set of SMA weldments, the GMA welding parameters for this set of weldments were selected based on results obtained from producing the initial weld wire evaluation weldment, PD-4837. Since these parameters had appeared to give fairly good results when used to produce PD-4837, they were selected without significant change for use in GMA welding this first set of 6-inch x 6-inch (15.24cm x 15.25cm) weldments.

Interpass temperature was intended to range between 250°F (121°C) and 275°F (135°C), with tempil sticks being used to check weldment temperatures. The problems of monitoring interpass temperature in this manner were previously described in the discussion of results of the first set of SMA weldments, SMA-1. Consequently, actual interpass temperatures for this first set of GMA weldments varied considerably as the weldments were completed. This variation is indicated, along with tensile test results, in Table XXI.

As in the case of the first set of SMA weldments, SMA-1, no special effort was made to control weld joint geometry accurately or to obtain good weld joint fit-up when these weldments were produced.

Results of nondestructive tests of these weldments indicated no rejectable defects.

The results of tensile tests of these weldments, shown in Table XX, indicate the yield strength of longitudinal all-weld-metal specimens varied from 137.8 Ksi (951 MPa) to 150.0 Ksi (1035 MPa). The higher strengths were obtained for lower preheat temperatures. Weld metal dilution effects are also considered to have contributed to the high strength of the mid-thickness specimen PD-4830-T3.

4.0 4.3 (Continued)

The transverse tensile test specimens tended to break in base metal areas where corresponding all-weld-metal tensile strengths had been greater than the strength of the base plate. Where corresponding all-weld-metal tensile strengths had been less than the strength of the base plate, failure occurred in weld metal. No indication was observed which would indicate that weld HAZ areas were weaker than the base plate or weld metal.

The results of Charpy V-notch impact tests of weld metal and weld HAZ areas are summarized in Table XXII. The average 72°F (22°C) impact energy for all-weld-metal specimens was 58 ft.-lbs. (79 joules), and 54 ft.-lbs. (73 joules) at 0°F (-17°C). The The average 72°F (22°C) impact energy for weld HAZ specimens was 80 ft.-lbs. (109 joules). Weldment heat input data are summarized in Table XXIII.

A photomacrograph of a section through weldment PD-4831 is shown in Figure 33 and a hardness traverse pattern through PD-4831 is shown in Figure 34; with Rockwell "C" hardness values for the various test points being summarized in Table XXIV.

The engineering fracture toughness of weldment PD-4931 was calculated at 171.0 Ksi $\sqrt{\text{in.}}$ (188 MPa· m 1/2) using the ASTM 5% secant offset method of analysis and an assumed crack depth equal to the maximum actual crack detph as measured after fracture. Using the crack size by compliance method of analysis the toughness was estimated at 200 Ksi $\sqrt{\text{in.}}$ (220 MPa· m 1/2).

The fracture surface and shape of the precracked area of specimen PD-4931 is shown in Figure 35, along with pertinent dimensional data. The load-displacement record of this specimen is shown in Figure 36.

3rd Set (GMA-2)

The second set of GMA weldments was welded using the parameters shown in Table VIII. A constant interpass temperature and a welding heat input energy which was as low and uniform as possible were used. The objective was to determine whether the losses in the strength of outer weld areas observed in each set of previous weldments were related to changes in welding heat input energies and interpass temperatures or due to weldment thickness or weld metal dilution effects.

It appeared from previous work performed by the Electric Boat division that a 250°F (121°C) minimum preheat may be necessary to avoid possible hydrogen cracking problems, but it was also felt that a maximum interpass temperature of 280°F (137°C) was necessary if a minimum yield strength of 140 Ksi (966 MPa) was to be attained. This resulted in a 30°F (-1.1°C) range in which welding could be performed. For most weld passes, welding heat input energy was limited to 30 Kj/in (12 Kj/cm) or less. It was felt that the parameters selected would result in the production of welds which would not be subject to hydrogen cracking while exhibiting a good combination of strength and toughness.

4.0 4.3 (Continued)

Again, as for previously discussed weldments, no special effort was made to control weld joint geometry accurately or to obtain good weld joint fit-up when these weldments were produced.

The results of nondestructive tests of these weldments indicated no rejectable defects.

Tensile test results, summarized in Table XXV, indicate the yield strength of 0.505-inch (1.28 cm) longitudinal all-weld-metal specimens varied from 130.3 Ksi (900 MPa) to 148.3 Ksi (1023 MPa). The high strength of specimen PD-4828-T3 was not surprising since other mid-thickness specimens from previously tested weldments had also exhibited exceptionally high strengths. The low strength of specimen PD-4828-T1 was, however, quite surprising - especially since the corresponding transverse tensile specimens PD-4824-TT1 exhibited a higher tensile strength than any other such specimen taken from weldment PD-4824 except the mid-thickness specimen while finally breaking in the weld metal. Also, specimen PD-4924-T5 was taken from weld metal deposited in a manner almost identical to PD-4824-T1 and yet this specimen exhibited a yield strength of 137.3 Ksi (947 MPa), very similar to that exhibited by specimens PD-4828-T2 and PD-4828-T4.

As a further investigation of these results a chemical analysis was performed on material from one half of specimen PD-4828-T1 and one half of specimen PD-4828-T2, and three additional 0.252-inch (0.64 cm) diameter tensile specimens were removed from weldment PD-4828 and tested. The chemical analysis results, included as part of Table III, revealed a carbon content of only

0.075 percent in the weld metal of PD-4828-T1 compared to 0.123 percent carbon content in PD-4828-T2. A check of the laboratory welding records for this weldment revealed the weld beads tested by Specimen PD-4828-T1 were made using weld wire from spool #806, having a carbon content of 0.08 percent. The weld beads tested by specimen PD-4828-T2 were similarly found to have been made using weld wire from spool #812, which had a carbon content of 0.09 percent. The lower carbon content of the weld wire used to deposit the weld beads tested by specimen PD-4828-T1 is felt to be the principal reason for the low yield and tensile strength exhibited by this specimen. The extra three 0.252-inch (0.64 cm) tensile specimens exhibited yield strengths ranging from 136.3 Ksi (940 MPa) to 139.8 Ksi (964 MPa), similar to the strength exhibited by specimens PD-4828-T2, -T4 and -T5. Although the weld beads tested by two of these extra specimens were also deposited using weld wire from spool #806, weld metal dilution by the relatively high carbon base plate material is felt to have occurred, thereby increasing the carbon content and keeping strength high.

The results of Charpy V-notch impact tests performed on these weldments are shown in Table XXVI. Transverse tests of weld HAZ areas averaged 84 ft.-lbs. (114 joules) at 72°F (22°C) and 75 ft.-lbs. (102 joules) at 0°F (-17°C). This was slightly higher than for either of the two previously completed sets of weldments. Longitudinal all-weld-metal Charpy specimens averaged 61 ft.-lbs. (83 joules) at 72°F (22°C) and 63 ft.-lbs. (86 joules) at 0°F (-17°C). These values are higher than obtained from the previous set of GMA weldments (Set GMA-1) but not as good as obtained from the set of SMA weldments (SMA-1). Weldment heat input data are summarized in Table XXVII.

A photo-macrograph of a section through weldment PD-4824 is shown in Figure 37 and a hardness traverse pattern is shown in Figure 38; with the Rockwell "C" hardness values for the various test points being summarized in Table XXVIII.

The engineering fracture toughness of weldment PD-4829 was calculated as 187.5 Ksi $\sqrt{\text{in.}}$ (206 MPa · m 1/2) using the ASTM 5% secant offset method of analysis and an assumed crack depth equal to the maximum actual crack depth as measured after fracture. Using the crack size by Compliance method of analysis the toughness was estimated as 252 Ksi $\sqrt{\text{in.}}$ (278 MPa · m 1/2). This is substantially greater than for the specimen from the first set of GMA weldments (GMA-1), but not as good as obtained from the specimen from the set of weldments produced using the SMA welding process (SMA-1).

The fracture surface and shape of the precracked area of specimen PD-4829 is shown in Figure 39, along with pertinent dimensional data. The load-displacement record of this specimen is shown in Figure 40.

4th Set (GMA-3)

The third set of GMA weldments was welded using the parameters shown in Table IX. The interpass temperature used for this set of weldments was considerably lower than that used in welding previously completed sets. Two different levels of heat input energies were used. Initially, welding was performed with a high heat input energy to determine if any problems of hydrogen embrittlement or hydrogen cracking would be encountered when high welding currents and high welding heat inputs were used with low preheat and interpass temperatures. The outer areas of these weldments were completed using a low heat input energy in an attempt to get maximum weld yield strength in these areas.

As in the case of all previously discussed weldments, no special effort was made to control weld joint geometry accurately or to obtain good weld joint fit-up when these weldments were produced.

The results of nondestructive tests of these weldments indicated no rejectable defects although occasional porosity was evident.

Tensile test results, summarized in Table XXIX indicate the weld metal yield strength of these weldments equaled or exceeded 145 Ksi (1001 MPa) for each specimen tested. One specimen, PD-4833-T3, taken from the low interpass, high heat input mid-thickness area of the weld exhibited a loss of elongation and a considerable drop in reduction of area. Also, a "spangle" or "fish-eye" was evident in the fracture surface. These factors were considered as an indication that some hydrogen embrittlement had occurred and that the use of a high heat input energy was detrimental to weld quality.

HAZ Charpy impact energies, summarized in Table XXX were all in excess of 50 ft.-lbs. (68 joules) and exceptionally good in the outer areas welded with the low heat input. All-weld metal charpy impact energies were also good, but still not equal to the values obtained from the first set of weldments (SMA-1). Welding heat input data was summarized in Table XXXI.

A photomacrograph of a section through weldment PD-4834 is shown in Figure 41 and a hardness traverse pattern is shown in Figure 42, with the R_c hardness values being summarized in Table XXXII.

Weldment PD-4835 was not properly precracked and an accurate estimate of the engineering fracture toughness could not be determined. The fracture surface and shape of the precracked area of this specimen are shown in Figure 43, along with pertinent dimensional data. The load-displacement record of this specimen is shown in Figure 44.

It should be reiterated that the specific procedures utilized for welding the last two sets of GMA weldments were intended primarily to demonstrate that different combinations of welding interpass temperature and energy input would produce weld metal having comparable tensile and fracture toughness properties when these combinations of interpass temperature and energy input resulted in nearly equivalent weld metal cooling rates. Additionally, set GMA-3 was used to determine if welding with high energy input, i.e., wire feed speeds ranging from 250-264 ipm (635 cm/pm-670 cm/pm) and corresponding welding current ranging from 325-365 amperes, would result in hydrogen cracking or hydrogen embrittlement.

These tests were not especially designed to establish the relationship between either yield strength or Charpy-V-notch energy absorption and cooling rate as a function of the energy input and preheat temperature utilized. However, an examination of the longitudinal tensile properties of the gas metal arc welds from all three sets of bars reveals that the properties obtained did not appear to follow the expected trend for this low alloy steel weld metal system. Other investigators[(10) (11)] have clearly demonstrated that the all-weld-metal tensile and yield strength can be expected to increase with an increasing cooling rate. Equations have been developed[(10)] which can be used to calculate the cooling rate from a specific temperature taking into account the metallurgical response of the particular alloying system, the effects of preheat and energy input.

As previously mentioned, the use of a contact pryometer for measuring interpass temperature on the last two sets of bars was considered to be more reliable than the use of tempil crayons used on the first two sets of bars. This was because the pre-heat/ interpass temperature could be measured at the point of welding rather than outside the weld joint. Since current and voltage for all weld beads deposited were recorded on chart recorders, the method of determining energy input was also considered to be quite accurate. Therefore the tensile specimens T-1, T-2, T-4 and T-5 from PD-4828 one of the 2nd set of GMA weldments were expected to have exhibited a minimum yield strength of 140 KSI (966MPa). Dorschu[10] has shown that a good approximation of the cooling rate of GMA welds can be calculated using the following expression:

$$dT/dt\binom{1000°F}{537°C} = M\,\frac{(T - To)^2}{E} + D$$

where:

dT/dt = Cooling rate (°F/Sec.) (°C/Sec.) M and D are constants

T = Temperature at which cooling rate is measured (1000°F) (537°C)

To = Initial temperature of plate (°F)(°C)

E = Welding energy input (KJ/in) (KJ/cm)

The cooling rate is seen to vary inversely with the energy input and directly with the square of the difference between the temperature at which the cooling rate is measured and the preheat temperature. Using the values of constants provided in reference (10) and substituting the values for To and E used in making the 2nd and 3rd sets of GMA weldments into the above expression the calculated cooling rates for both are found to be in the order of 50°F (10°C)/sec. to 70°F (21°C)/sec. Accordingly, the yield strength of longitudinal tensile specimens taken from both sets of bars should have met or exceeded 140 KSI (966 MPa). The fact that all tensiles tested from PD-4833 (GMA-3) did and only one of the outer specimens from PD-4828 (GMA-2) exhibited a yield strength as high as 140 KSI (966 MPa) is not readily explained. However, this wide distribution of all-weld-metal yield strength values has on occasion been experienced by other investigators[(2)(11)] involved in GMA welding 2-inch (5.07 cm) thick HY-150 plate, although where a sufficient number of specimens have been tested the relationship between yield strength and weld-metal cooling rate is clearly defined. This characteristic of the HY-150 weld metal yield strength to be influenced by cooling rate is also modified by such factors as its tempering behavior and changes in composition due to dilution.

4.0 4.3 (Continued)

The Rockwell C hardness traverses, made on macro sections from bars PD-4824 and PD-4834 which were the corresponding bars for PD-4828 and PD-4833, i.e., they were welded at the same time under like conditions, reflect the variation in strength level achieved on the third and fourth sets of weldments. For example the hardness traverses on the outer portion of a macro from PD-4824 in the area corresponding to longitudinal tensiles T-1 and T-5 from PD-4828 showed the weld metal to have an Rc hardness range of 31-32 and 32-35 respectively. Specimen PD-4828-T-1 exhibited a yield strength of only 130 KSI (897 MPa), while specimen PD-4828-T-5 was somewhat higher in strength at 137 KSI (945 MPa). The highest weld metal hardness readings on PD-4824 (PD-4828) were in the order of 36-38 Rc. In contrast the hardness traverses on that macro from PD-4834 (PD-4833) showed the hardness of the weld metal alone to vary from a low of 36 Rc to a high of 45 Rc. Tensile specimen T-4 from PD-4833 which exhibited a tensile strength of 165 KSI (1139 MPa) and a yield strength of 153 KSI (1055 MPa) appears to have had a corresponding hardness of Rc 40-45 as shown by Figure 38 and Table XXXII. Both tensile speicmens T-4 and T-2 from the near midthickness areas of PD-4833 were located in those areas where the weld layers were deposited at a high level of wire feed speed and current, i.e., 250-264 ipm (635-670cm/m) and 315-365 amperes, in contrast to the outer or near-surface weld beads from which specimens

T-1 and T-5 were removed. Figure 38 illustrates the increase in weld bead cross section which resulted from the use of the higher welding parameters. It was of interest to note that although a higher heat input was used for the near mid-thickness weld layers, i.e., 47-51 KJ/in (18.5-20 KJ/cm) than for the outside weld layers, 37-39 KJ/in (14.6-15.3 KJ/cm), the strength and hardness of the mid-thickness weld layers were still somewhat higher. This is believed to have resulted for the following reasons: (1) although the energy input was higher, the weld beads still cooled relatively fast because of the low preheat/interpass temperature utilized, 210-212°F (99-100°C). In addition, increasing wire feed speed and current with the GMA process is known to not only increase the overall bead cross-section but causes an increase in the pappila of the nugget. The pappila area being longer and narrower lends to solidify rapidly. (2) The HY-150 weld metal exhibits a very high strength when initially deposited at a cooling rate fast enough to form martensite. However, the strength and hardness of a multipass weld is appreciably weakened after exposure to a series of weld thermal cycles from subsequent weld passes. This is considered to be the primary reason a rather wide distribution existed between the tensile and yield strength obtained on the last two sets of gas metal arc weldments, and for the narrower differences in strength which existed between near mid-thickness and near surface tensiles of a single weld joint. Therefore, it appears that those weld passes deposited in PD-4833 at a higher wire feed speed and current were not as markedly influenced by subsequent heat cycles, as weld passes deposited near the surface at a lower level of wire feed speed and current judging from the results of the tensile and hardness tests.

As further evidence of the difference in strength which was found to exist between sets GMA-2 and GMA-3, was the fact that of six transverse tensile specimens removed from PD-4824 (the corresponding bar for PD-4828), all but one broke in the weld metal, only the mid-thickness specimen broke in the base material. On the other hand of the five transverse tensiles tested from PD-4834 (the corresponding bar for PD-4833) all but one (a top near surface specimen) broke in the base metal.

No attempt was made to investigate further the effects of the multiplicity of thermal cycles had on the microstructure of the weld metal through metallographic analyses, as this work was not considered to be within the scope of this program. In addition an in-depth study of this subject is presented in reference(12).

The values of energy absorption for longitudinal Charpy-V-notch impact tests performed on PD-4824(set GMA-2) compared with those recorded for PD-4834 (set GMA-3) were on the average higher than those tested from the latter at both test temperatures, i.e., 72°F (22°C) and 0°F (-17°C). At 72°F (22°C) near top and bottom surface specimens from PD-4834 exhibited toughness values comparable to those obtained on PD-4824. However at 0°F (-17°C) specimens removed from the 1/8 and 7/8 thickness from PD-4824 showed no loss in toughness while those from PD-4834 did suffer a loss in toughness. Longitudinal Charpy-V-notch tests on weldments SMA-1 and GMA-1 also exhibited a loss in toughness between 72°F (22°C) and 0°F (-17°C) however both individual and average values of energy absorption were higher than on PD-4834. An analysis of this data as well as that of preliminary weldments PD-4836 and PD-4837 indicates that Charpy-V-notch impact properties can be expected to vary inversely as a function of the yield strength, within a given yield strength range, for welds deposited with either the SMA or GMA processes.

After an analysis of the data from Tasks I, II and III was completed the semi-automatic GMA welding process was recommended for use in all Task IV welding, and subsequently for the production welding of motor case Y rings and nozzles flanges with the following reasons as justification:

4.0 4.3 (Continued)

1. Experience gained by the Electric Boat division and other fabricators in developing welding processes and techniques for joining HY-150 has demonstrated that the manual shielded metal arc welds are more sensitive to cracking and/or hydrogen embrittlement than GMA welds.

2. In addition to continuous maintenance of preheat during welding, which is required for both types of filler metal, the shielded metal arc 14018 electrode has been shown to require a post weld soaking period at preheat temperature.

3. To maintain the moisture content of the SMA electrode below 0.1%, it is recommended by the manufacturer that the electrode exposure time be 20 minutes maximum, while the bare wire electrode used with the GMA process can be left up to eight hours on the wire feeder with no deleterious effects.

4. The use of the GMA procedure for welding motor case case Y rings and nozzle flanges should provide savings of at least 25% over shielded metal arc welding. This saving accrues through the higher deposition rate and higher operator factor inherent with the semi-automatic gas metal arc process.

4.0 4.3 (Continued)

The optimum welding procedure developed for welding HY-130 in the flat position with the semi-automatic spray arc GMA process is shown in Table XXXIII. The wire feed speed and welding current selected has been restricted to a maximum of 200 ipm (508 cm/min) and 310 amperes respectively, to facilitate good weld metal soundness, i.e., wire feed speed and welding current in excess of 245 ipm (622 cm/in) and 360 amperes have been shown to increase the incidence of porosity in low alloy steel weld metal. For welding HY-150 steel with the GMA process, it is recommended that the wire feed speed be maintained at a level of 200 ipm (507 cm/min) maximum, because higher wire feed speeds have been demonstrated[(2)(3)] to encourage hydrogen damage. Specifically, prolonged restraint promotes the diffusion of the available hydrogen to areas of stress concentration. Wire feed speeds of 210-250 ipm (533-635 cm/min) deepended the papilla and help hydrogen to be entrapped in it. In addition, it is possible that a deep papilla serves as a stress concentration point in itself.

The welding parameters and fabrication controls contained in Table XXXIII were selected as being optimum, since they are expected to produce GMA welds exhibiting reproducible acceptable weld quality, and the best combination of weld metal strength and toughness in 6-inch (15.24 cm) material. Adherence to the range of plate temperature and maximum heat input specified should make possible a cooling rate fast enough to

4.0 4.3 (Continued)

provide a mean yield strength of 140 KSI (966 MPa) with a corresponding mean Charpy-V-notch energy absorption rate of 55 ft.-lbs. (75 Joules) @ 72°F (22°C) and 47 ft.-lbs. (64 Joules) @ 0°F (-17°C). The present specification for Type MIL-140S bare wire, issued by the Naval Ships System Command, i.e., MI-30BE requires a minimum average Charpy-V-notch impact value of 50 ft.-lbs. (68 Joules) @ 30°F (-1°C) for an all-weld metal yield strength range of 135 KSI (932 MPa) to 145 KSI (1000 MPa).

5.0 CONCLUSIONS

5.1 The welding techniques developed in this program for welding 6-inch (15.24cm) thick HY-150 steel in the flat position with the spray gas metal arc and shielded metal arc processes can be expected to consistently produce welds of good soundness and excellent mechanical properties.

5.2 Results of this program indicate that both the shielded metal arc and semi-automatic gas metal arc processes can be used to fabricate low cost HY-150 rocket motor nozzle attachment flanges and 'Y' rings using a rolled and welded procedure, as the weld metal deposited by each process exhibits excellent toughness at yield strength levels of 135 Ksi (930 MPa) - 145 Ksi (1000 MPa).

5.3 The shielded metal arc electrode used in this program can be expected to produce welds with superior toughness to that produced by gas metal arc welds as determined by the results of Charpy V-notch and edge notched full thickness slow bend tests.

5.4 Unstable crack propagation at stress levels below yield will not occur in structures fabricated of this material, as demonstrated by the slow bend fracture toughness tests. Some plastic deformation preceded crack extension in all specimens. The critical stress intensity factor K_{IC} could not be obtained even in this 6-inch (15.24cm) thickness of material by the standard ASTM test method.

5.0 (Continued)

5.5 The goal of a minimum yield strength of 140,000 Psi (966 MPa) for the 6-inch (15.24cm) thick HY-150 plate produced for this program was not attained. It is probable that this was the result of insufficient quenching action, as the plates were immersed horizontally into a wide, shallow tank of flowing water which allowed large steam bubbles to form, with reduced heat transfer out of the plates.

5.6 In addition, the presence of a band of inclusions through the center of each plate indicates that melting and/or processing require refinement if a cleaner grade of metal is required for the intended application.

6.0 RECOMMENDATIONS

Material of the section sizes required by NASA might better be obtained by rolling directly to size, rather than by rolling plate which is subsequently cut to the sizes required. Bars, rather than plates, would tend to quench out more thoroughly or quickly, so that hardness is more uniform through the section thickness.

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TABLE I - Chemical Composition of 6" (15.24cm) Thick HY-150 Plate, U.S. Steel Heat #5P3947

	Analysis, % By Weight											
	%C	%Mn	%P	%S	%Si	%Cu	%Ni	%Cr	%Mo	%V	%Ti	%Al
Ladle Analysis	0.11	0.81	0.007	0.005	0.23	0.06	4.95	0.57	0.50	0.07	0.01	N.R.
Check Analysis Front	0.11	0.82	0.012	0.010	0.25	0.06	4.84	0.55	0.49	0.07	0.002	N.R.
Check Analysis, Rear	0.10	0.82	0.011	0.010	0.26	0.06	4.84	0.57	0.49	0.07	0.001	N.R.
E.B. Div Analysis	0.13	0.83	0.011	0.005	0.19	N.D.	5.03	0.54	0.47	0.064	N.D.	0.02
MIL-S-24371 (Modified for Carbon and Sulfur)	0.09-0.13	0.60-0.90	0.10	0.10	0.20-0.35	0.25 max.	4.75-5.25	0.40-0.70	0.30-0.65	0.05-0.10	0.02 max.	N.D.

N.D. - Not determined

N.R. - Not recorded

TABLE II - Mill Heat Treating Data, Plates F-4602 and F-4603

Plate F-4602

1. Initial Heat Treatment:
   a. 1670°F[1] (910°C)/2 Hrs. @ Temp.
   b. Water Quench
   c. 1499°F (815°C)/2 Hrs. @ Temp.
   d. Water Quench
   e. 995°F (535°C)/2 Hrs. @ Temp.
   f. Water Quench

2. 1st and Final Re-Heat Treatment:
   a. 1499°F (815°C)/2 Hrs. @ Temp.
   b. Water Quench
   c. 995°F (535°C)/2 Hrs. @ Temp.
   d. Water Quench

Plate F-4603

1. Initial Heat Treatment:
   a. 1657°F[1] (902°C)/2-1/2 Hrs. @ Temp.
   b. Water Quench
   c. 1504°F (817°C)/2-1/2 Hrs. @ Temp.
   d. Water Quench
   e. 995°F (535°C)/2 Hrs. @ Temp.
   f. Water Quench

2. 1st Re-Heat Treatment:
   a. 1010°F (543°C)/2 Hrs. @ Temp.
   b. Water Quench

3. 2nd Re-Heat Treatment:
   a. 1020°F (548°C)/2 Hrs. @ Temp.
   b. Water Quench

4. 3rd Re-Heat Treatment:
   a. 1508°F (820°C)/2 Hrs. @ Temp.
   b. Water Quench[2]
   c. 1004°F (540°C)/2 Hrs. @ Temp.
   d. Water Quench

5. 4th and Final Re-Heat Treatment:
   a. 1505°F (820°C)/2 Hrs. @ Temp.
   b. Water Quench[3]
   c. 1004°F (540°C)/2 Hrs. @ Temp.
   d. Water Quench

Notes: (1) Plates brought up to temperature at 1 hr./inch (2.54cm) in all cases.

(2) Plate lowered into circulating water.

(3) Plate lowered and moved as water circulated.

TABLE III - Chemical Composition of HY-150 Weld Wire and As-Deposited Weld Metal

Items Tested and Source

Analysis, % By Weight

Items Tested and Source	%C	%Mn	%P	%S	%Si	%Cu	%Ni	%Cr	%Mo	%V	%Ti	%Al	%O_2	%N_2	%H_2
a. GMA Bare Wire, Airco 0.062"(0.16cm), Heat #1P1338															
Airco Analysis	0.10	1.79	0.007	0.006	0.42	0.080	2.00	0.83	0.54	0.01	0.018	0.001	52 [3]	106 [3]	2.6 [4]
EB Analysis															
Spool #464	0.09	1.82	N.D.	N.D.	N.D.	N.D.	2.09	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Spool #812	0.09	1.81	"	"	"	"	2.07	"	"	"	"	"	"	"	"
Spool #806	0.08	1.81	"	"	"	"	2.07	"	"	"	"	"	"	"	"
b. SMA Electrode, McKay 1/8"(0.32cm), Heat #422W2201, Lot #281995, Batch #1672															
McKay Analysis (As Deposited)	0.085	0.88	0.004	0.004	0.37	N.D.	3.64	0.52	0.80	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
c. SMA Electrode, McKay 3/16"(0.47cm), Heat #422W2201, Lot #29179, Batch #2409															
McKay Analysis (As Deposited)	N.D.	0.96	N.D.	N.D.	0.37	N.D.	3.53	0.46	0.78	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
d. EB Analysis from PD-4828, All Weld Tensiles															
TT1	0.075	1.58	0.010	0.004	0.32	0.060	2.31	0.82	0.53	0.01	"	0.001	"	"	"
TT2	0.123	1.62	0.010	0.006	0.31	0.055	2.45	0.81	0.54	0.01	"	0.001	"	"	"

General Dynamics
Electric Boat Division

TABLE IV - Welding Procedure Record Sheet for Test Plate No. PD-4836 (SMA)

Contract or Job No: NAS 3-12056

Shop Order No.: 3366-244

Title of Program: NASA 6-Inch (15.24cm) HY-130 Welding Study - Preliminary Test Plate (SMA-2"(5.08cm) Thick

Date of Record: 1/16/70

Weldment No: PD-4836A

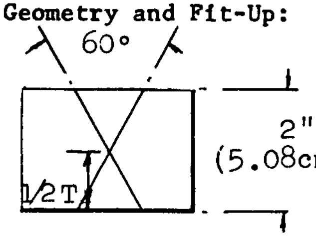
WELD JOINT DETAILS

Method of Preparation:
Flame Cut and Ground Clean

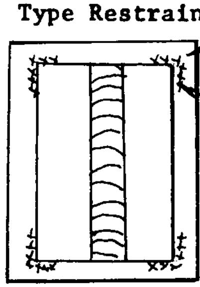
Pre-Weld Cleaning:
Wire Brush (Stainless)

Interpass Cleaning:
Slag Pick & Wire Brush

Geometry and Fit-Up:



Type Restraint:



Electrode Shape or Tip Data:

FIXED PARAMETERS	Initial	As Varied
Process	SMA	
Manual, Auto, etc	Manual	
Polarity	DCRP	
Position	Flat	
Base Material	HY-80 to	Same
Source	Storage Rack	
Heat Treatment	Quenched & Tempered	
Thickness, Size	2"x18"x6"(5.08cm x 45.72cm x 15.29cm)	
Filler Wire	E-14018 AW	
Diameter	1/8" (0.32cm)	3/16" (0.47cm)
Producer & Heat	McKay #422W2201	McKay #422W2201
Lot & Spool No.		
Torch		
Gas or Flux		
Backing Material		
Backing Gas		
Heat Input Limits (Max)	37KJ/in 15KJ/cm	32KJ/in 12KJ/cm
Preheat	200°F (93°C) Min.	
Postheat	Cont. 200°F (93°C) min.-held 16 hrs after finish	
Interpass	300°F (148°C) Max.	
Welding Head		
Wire Feeders		
Meters & Locations	200 amp. Tong Meters, E.B. #R	
Recorders	None	

Special or Non-st'd Devices:
None

Mat'l Handling & Storage:
As received cans put into 300°F (148°C) drying oven immediately upon opening max. exposure outside oven= 20 minutes.

Cognizant Engineer: P. Schmidt

Weldor: D. Main

REQUIRED SAMPLES (Take and Identify)

X	Wire-Start of Joint
X	Wire-Start of Spool
	Wire-Start of Shift
	Other:

REQUIRED INSPECTION

X	Fit-Up,	[X]	Vis	[ ]	LP
X	Root,	[ ]	LP	[X]	MP
X	Back-side	[ ]	LP	[X]	MP
X	Final,	[X]	LP	[X]	MP
		[X]	RT	[X]	UT
	Intermediate	[ ]	LP	[ ]	MP

APPLICABLE SPECS.

Welding Procedure:

Base Material: MIL-S-24371 (SHIPS)

Weld Filler Wire: MI-30 CE/1, Incl. Appx. A

Radiographic Inspector: NAVSHIPS 250-1500-1

Ultrasonic Inspection: NAVSHIPS 0900-006-3010

General Dynamics
Electric Boat Division

TABLE IV (Continued) - Welding Procedure Record Sheet for Test Plate No. PD-4836 (SMA)

--- DEPOSITION SEQUENCE AND FOLLOWING DATA FOR EACH WELD BEAD---

Pass No.	Arc Amp.	Arc Volts	Travel* ipm (cm/pm)	Wire ipm	Pulsed-Arc Peak	Pulsed-Arc Bkgd.	Cup Size	Total cfh	Cup/Work inches	Tip/Work inches	Weld Start Temp. °F (°C)	Comments (Repairs, etc.)
1-16	120/130	20/24	4-1/2 11.4	--	--	--	--	--	--	--	250 121 Min.	1/8" (0.32cm) Electrode
17-32	235/245	20/23	9-1/2 24.1	--	--	--	--	--	--	--	"	3/16" (0.47cm) Electrode
33-53	120/130	20/24	4-1/2 11.4	--	--	--	--	--	--	--	"	1/8" (0.32cm) Electrode
54-85	235/245	20/23	9-1/2 24.1	--	--	--	--	--	--	--	"	3/16" (0.47cm)
*Typical												

General Dynamics
Electric Boat Division

TABLE V - Welding Procedure Record Sheet for Test Plate No. PD-4837 (GMA)

Contract or Job No:	NAS #-12056
Shop Order No.:	3366-243
Title of Program:	NASA HY-130 Welding Study - Preliminary
Test Plate No.:	PD-4837 (GMA)
Date of Record:	1/14/70
Weldment No:	PD-4837
Cognizant Engineer:	P. Schmidt
Weldor:	D. Main (Root) R. Root (Fill)

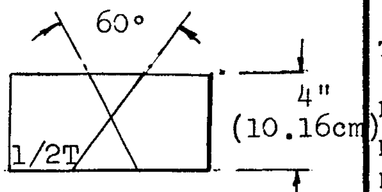
WELD JOINT DETAILS

Method of Preparation: Joint Surfaces Flame Cut and Ground

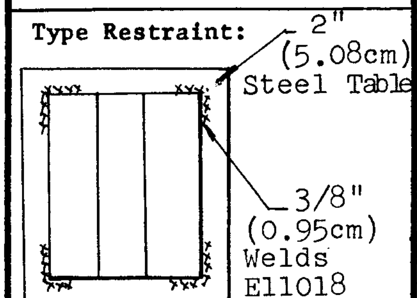
Pre-Weld Cleaning:

Interpass Cleaning: Slag-picked and hand wire brushed.

Geometry and Fit-Up:



Type Restraint:



Electrode Shape or Tip Data: 0.071" (0.18cm) dia. tube

FIXED PARAMETERS	Initial	As Varied
Process	SMA	GMA
Manual, Auto, etc	Manual	Semi-Automatic
Polarity	DCRP	DCRP
Position	Flat	Flat
Base Material	HY-80 to	Same
Source	Yard Storage Area	
Heat Treatment		
Thickness, Size	4"x18"x6"(10.16cm x 45.72cm x 15.24cm)	
Filler Wire	McKay E-14018 AW	Airco AX-140
Diameter	1/8" (0.32cm)	0.062" (0.16cm)
Producer & Heat	#422W2201	#1P1338
Lot & Spool No.	#281995, #1672	Control 795 & 799
Torch		Linde ST-5
Gas or Flux		Argon/2% Oxygen
Backing Material		
Backing Gas		
Heat Input Limits (Max.)	37KJ/in 14.5KJ/cm	50KJ/in 19.7KJ/cm
Preheat	250/300°F, (121/148°C)	
Postheat	Cont. 250°F (121°C) min. held 16 hrs.	after finish
Interpass	300°F (148°C) Max.	
Welding Head		
Wire Feeders		
Meters & Locations	200 amp. Tong Meters, E.B. #R	
Recorders		

Special or Non-st'd Devices: None

Mat'l Handling & Storage: Bare wire covered with sealed plastic bag (no desicant) each night.

REQUIRED SAMPLES (Take and Identify)

	Wire-Start of Joint
X	Wire-Start of Spool
	Wire-Start of Shift
	Other:

REQUIRED INSPECTION

	Fit-Up,	☐ Vis	☐ LP
X	Root,	☐ LP	☒ MP
X	Back-side	☒ LP	☒ MP
X	Final,	☒ LP	☒ MP
		☒ RT	☒ UT
	Intermediate	☐ LP	☐ MP

APPLICABLE SPECS.

Welding Procedure:

Base Material: MIL-S-24371 (SHIPS)

Weld Filler Wire: MI-30 CE/1, Incl. Appx. A

Radiographic Inspector: NAVSHIPS 250-1500-1

Ultrasonic Inspection: NAVSHIPS 0900-006-3010

TABLE V (Cont'd) - Welding Procedure Record Sheet for Test Plate No. PD-4837 (GMA)

---DEPOSITION SEQUENCE AND FOLLOWING DATA FOR EACH WELD BEAD---

Pass No.	Arc Amp.	Arc Volts	Travel* ipm (cm/pm)	Wire ipm (cm/pm)	Pulsed-Arc Peak	Pulsed-Arc Bkgd.	Cup Size	Total cfh (cmh)	Cup/Work inches (cm)	Tip/Work inches (cm)	Weld Start Temp. °F (°C)	Comments (Repairs, etc.)
1 & 2	120/130	20/24	4-1/2 11.4	--	--	--	--	--	--	--	250 121 Min.	1/8" (0.32cm) (SMA)
3-125	290/310	24/25	9 24	188 477	--	--	#8#10	45 1.27	1/2" 1.27	5/8" 1.59	"	1/16" (0.16cm) Bare Wire
*Typical												

General Dynamics
Electric Boat Division

TABLE VI - Welding Parameters for Weldments PD-4825, PD-4826 and PD-4827

Contract or Job No:	NAS 3-12056
Shop Order No.:	3366-244
Title of Program:	NASA 6-Inch (15.24 cm) HY-150 Welding Study - Task III
Date of Record:	4/21/70
Weldment No:	PD-4825,-26,-27
Cognizant Engineer:	P. Schmidt
Weldor:	D. Main/ W. Graham

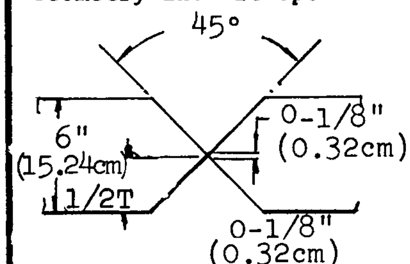
WELD JOINT DETAILS

Method of Preparation:
Flame Cut and Ground Clean

Pre-Weld Cleaning:
Wire Brush

Interpass Cleaning:
Slag Pick And Wire Brush

Geometry and Fit-Up:



Type Restraint:
None

Electrode Shape or Tip Data:
--

FIXED PARAMETERS	Initial	As Varied
Process	SMA	
Manual, Auto, etc	Manual	
Polarity	DCRP	
Position	Flat	
Base Material	HY-150 to	Same
Source	U.S.Steel Corp.	
Heat Treatment	Quenched & Tempered	
Thickness, Size	x6"x24"(15.24cm x 15.24cm x 60.9cm)	
Filler Wire	E-14018 AW	
Diameter	1/8"(0.32cm)	3/16"(0.47cm)
Producer & Heat	McKay #422W2201	
Lot & Spool No.	#281995 - #1672	#291795 - #2409
Torch	--	
Gas or Flux	--	
Backing Material	--	
Backing Gas	--	
Heat Input Limits(Max).	40KJ/in 15.7KJ/cm	
Preheat	250°F(121°C)Min.	
Postheat	Cont.250°F(121°C)min.-held 16 hours after finish.	
Interpass	300°F (148°C)Max.	
Welding Head	--	
Wire Feeders	--	
Meters & Locations	EB #200R	EB #300R
Recorders		

Special or Non-st'd Devices:
None

Mat'l Handling & Storage:
As received cans put into 300°(148°C) drying oven immediately upon opening. M Max. exposure outside oven - 20 min.

REQUIRED SAMPLES (Take and Identify)

	Wire-Start of Joint
	Wire-Start of Spool
	Wire-Start of Shift
	Other:

REQUIRED INSPECTION

X	Fit-Up,	[X]	Vis	[ ]	LP
X	Root,	[ ]	LP	[X]	MP
X	Back-side	[ ]	LP	[X]	MP
X	Final,	[X]	LP	[X]	MP
		[X]	RT	[X]	UT
	Intermediate	[ ]	LP	[ ]	MP

APPLICABLE SPECS.

Welding Procedure:
--

Base Material:
MIL-S-24371 (SHIPS)

Weld Filler Wire:
MI-30 CE/1,Incl.Appx. A

Radiographic Inspector:
NAVSHIPS 250-1500-1

Ultrasonic Inspection:
NAVSHIPS 0900-006-3010

General Dynamics
Electric Boat Division

TABLE VI (Cont'd) - Welding Parameters for Weldments PD-4825, PD-4826 and PD-4827

---DEPOSITION SEQUENCE AND FOLLOWING DATA FOR EACH WELD BEAD---

Pass No.	Arc Amp.	Arc Volts	Travel* ipm (cm/pm)	Wire ipm	Pulsed-Arc Peak	Pulsed-Arc Bkgd.	Cup Size	Total cfh	Cup/Work inches	Tip/Work inches	Weld Start Temp. °F (°C)	Comments (Repairs, etc.)
1&2	120/130	23/25	4-1/2 11.4	--	--	--	--	--	--	--	250 121 Min.	1/8" (0.32cm) Electrode
3-59	230/240	20/23	7 17.8	--	--	--	--	--	--	--	"	3/16" (0.47cm) Electrode
60-307	"	"	11 27.9	--	--	--	--	--	--	--	"	" "

*Typical

General Dynamics
Electric Boat Division

TABLE VII - Welding Parameters for Weldments PD-4830, PD-4831 and PD-4931

Contract or Job No:	NAS #-12056
Shop Order No.:	3366-244
Title of Program:	NASA 6-Inch (15.24 cm) HY-150 Welding Study - Task III
Date of Record:	3/26/70
Weldment No:	PD-4830,-31
Cognizant Engineer:	P. Schmidt
Weldor:	R. Root, Jr.

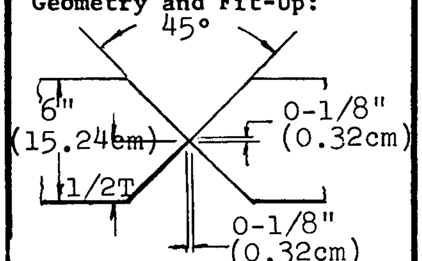
WELD JOINT DETAILS

Method of Preparation:
Flame Cut and Ground Clean.

Pre-Weld Cleaning:
Wire Brush

Interpass Cleaning:
Slag Pick And Wire Brush

Geometry and Fit-Up:



Type Restraint:

Electrode Shape or Tip Data: .071" (0.18cm) Dia. Tube and 0.070" (0.18cm) Dia. Tip.

FIXED PARAMETERS	Initial	As Varied
Process	SMA	GMA
Manual, Auto, etc	Manual	Semi-Automatic
Polarity	DCRP	DCRP
Position	Flat	Flat
Base Material	HY-150	to Same
Source	U.S. Steel Corp.	
Heat Treatment	Quenched & Tempered	
Thickness, Size	6"x6"x24"(15.24cm x 15.24cm x 60.9cm)	
Filler Wire	McKay 14018 AW	Airco AX-140
Diameter	1/8" (0.32cm)	0.062" (0.16cm)
Producer & Heat	#422W2201	#1P1338
Lot & Spool No.	#281995, #1672	
Torch	--	Linde ST-5
Gas or Flux	--	Argon/2% Oxygen
Backing Material	--	--
Backing Gas	--	--
Heat Input Limits (Max)	35KJ/in 13.7KJ/cm	45KJ/in 17.6KJ/cm
Preheat	250°F(121°C) Min.	250°F(121°C) Min.
Postheat	Cont. 250°F(121°C) Min.-held 16 hours	
Interpass	300°F(148°C) Max.	after finish.
Welding Head	--	--
Wire Feeders	--	Linde AWM-11-S
Meters & Locations	EB #200R	Same
Recorders	--	--
Power Supply	P & H	Linde SVI-750

Special or Non-st'd Devices:
Automatic preheat and post heat control.

Mat'l Handling & Storage:
a) Bare wire covered with plastic cover overnight.
b) Weldment @300°F(148°C) overnight.

REQUIRED SAMPLES (Take and Identify)

X	Wire-Start of Joint
	Wire-Start of Spool
	Wire-Start of Shift
	Other:

REQUIRED INSPECTION

X	Fit-Up,	[X] Vis [ ] LP
X	Root,	[ ] LP [X] MP
X	Back-side	[ ] LP [X] MP
X	Final,	[ ] LP [X] MP; [ ] RT [X] UT
	Intermediate	[ ] LP [ ] MP

APPLICABLE SPECS.

Welding Procedure: --

Base Material: MIL-S-24371 (SHIPS)

Weld Filler Wire: MI-30 BE/1

Radiographic Inspector: NAVSHIPS 250-1500-1

Ultrasonic Inspection: NAVSHIPS 0900-006-3010

TABLE VII (Cont'd) - Welding Parameters for Weldments PD-4830, PD-4831 and PD-4931

---DEPOSITION SEQUENCE AND FOLLOWING DATA FOR EACH WELD BEAD---

Pass No.	Arc Amp.	Arc Volts	Travel* ipm (cm/pm)	Wire ipm (cm/pm)	Pulsed-Arc Peak	Pulsed-Arc Bkgd.	Cup Size	Total cfh (cmh)	Cup/Work inches (cm)	Tip/Work inches (cm)	Weld Start Temp. °F (°C)	Comments (Repairs, etc.)
1 & 2	120/130	20/24	4-1/2 11.4	--	--	--	--	--	--	--	250 121 Min.	1/8" (0.32cm) Electrode
3-25	280/290	25/26	9-1/2 24.1	175/180 444/457	--	--	#8/#10	45 1.27	5/8" 1.59	3/4" 1.90	"	0.062" (0.16cm) Electrode
26-49	280/290	24/25	12 30.48	"	--	--	#8	"	1/2" 1.27	5/8" 1.59	"	" "
50-276	280/290	25/26	12-1/2 31	"	--	--	#10	"	"	"	"	" "

*Typical

General Dynamics
Electric Boat Division

TABLE VIII - Welding Parameters for Weldments PD-4824, PD-4828 and PD-4829 (Set GMA-2)

Contract or Job No: NAS 3-12056

Shop Order No.: 3366-244

Title of Program: NASA 6-Inch (15.24cm) HY-150 Welding Study - Task III

Date of Record: 6/1/70

Weldment No: PD-4824, -28 -29

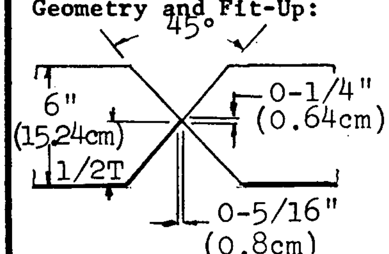
WELD JOINT DETAILS

Method of Preparation: Flame Cut & Ground Clean.

Pre-Weld Cleaning: Wire Brush

Interpass Cleaning: Slag Pick and Wire Brush

Geometry and Fit-Up:



Type Restraint: None

Electrode Shape or Tip Data: 0.070"(0.18cm) Dia. Tip.

FIXED PARAMETERS	Initial	As Varied
Process	SMA (Beads 1 & 2)	GMA(Beads 3 & on)
Manual, Auto, etc	Manual	Semi-Automatic
Polarity	DCRP	DCRP
Position	Flat	Flat
Base Material	HY-150	to Same
Source	U.S. Steel Corp.	
Heat Treatment	Quenched&Tempered	
Thickness, Size	6"x6"x24"(15.24cm x 15.24cm x 60.9cm)	
Filler Wire	McKay E-14018 AW	Airco AX-140
Diameter	1/8" (0.32cm)	0.062" (0.16cm)
Producer & Heat	#422W2201	#1P1338
Lot & Spool No.	#281995, #1672	
Torch	--	Linde ST-5
Gas or Flux	--	Argon/2%Oxygen
Backing Material	--	--
Backing Gas	--	--
Heat Input Limits (Max.)	35KJ/in 13.7KJ/cm	45KJ/in 17.6KJ/cm
Preheat	225°F (117°C)	225-300°F(117-148°C)
Postheat	Cont.250°F(121°C)Min.-held 16 hours	
Interpass	275°F(135°C)Max.	225-300°F(117-148°C)
Welding Head	--	--
Wire Feeders	--	Linde AWM-11-S
Meters & Locations	EB #R.-200a	EB #R.-200a
Recorders	--	--
Power Supply	P & H	Linde SVI-750

Special or Non-st'd Devices: Automatic preheat and post heat control.

Mat'l Handling & Storage:
a) Bare wire covered with plastic cover overnight.
b) Weldment @300-400°F(148-204°C) between all shifts and for 16 hrs.minimum after finish

Cognizant Engineer: P. Schmidt

Weldor: R. Root, Jr.

REQUIRED SAMPLES (Take and Identify)

X	Wire-Start of Joint
	Wire-Start of Spool
	Wire-Start of Shift
	Other:

REQUIRED INSPECTION

X	Fit-Up,	[X] Vis	[ ] LP
X	Root,	[ ] LP	[X] MP
X	Back-side	[ ] LP	[X] MP
X	Final,	[X] LP	[X] MP
		[X] RT	[ ] UT
	Intermediate	[ ] LP	[ ] MP

APPLICABLE SPECS.

Welding Procedure:

Base Material: MIL-S-24371 (SHIPS)

Weld Filler Wire: MI-30-BE/1

Radiographic Inspector: NAVSHIPS 250-1500-1

Ultrasonic Inspection: NAVSHIPS 0900-006-3910

General Dynamics
Electric Boat Division

TABLE VIII (Cont'd) - Welding Parameters for Weldments PD-4824, PD-4828 and PD-4829 (Set GMA-2)

---DEPOSITION SEQUENCE AND FOLLOWING DATA FOR EACH WELD BEAD---

Pass No.	Arc Amp.	Arc Volts	Travel* ipm (cm/pm)	Wire ipm (cm/pm)	Pulsed-Arc Peak	Pulsed-Arc Bkgd.	Cup Size	Total cfh (cmh)	Cup/Work inches (cm)	Tip/Work inches (cm)	Weld Start Temp. °F (°C)	Comments (Repairs, etc.)
1-2	145-155	--	--	--	--	--	--	--	--	--	250-260 121-127	1/8" (0.32cm) (SMA)
3-16	270-280	25	9-1/2 24.1	176 447	--	--	#8#10	45 1.27	1/2" 1.27	5/8" 1.59	225-235 107-111	1/16" (0.16cm) Bare Wire
17-40	270-280	"	12 30.48	" "	--	--	#8	" "	" "	" "	245-255 118-123	" " " "
41-54	270-280	"	15 38.2	" "	--	--	#8	" "	" "	" "	280-300 138-168	" " " "
55-303	270-280	"	" "	" "	--	--	#10	" "	" "	" "	" "	" " " "

*Typical

General Dynamics
Electric Boat Division

TABLE IX - Welding Parameters for Weldments PD-4833, PD-4834, and PD-4835

NAS 3-12056 Contract or Job No:	Title of Program: NASA 6-Inch (15.24cm) HY-150 Welding Study - Task III	Date of Record: 7/8/70
Shop Order No.:3366-244		Weldment No: PD-4833, PD-4834,-35

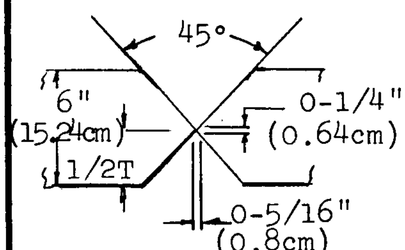
WELD JOINT DETAILS

Method of Preparation: Flame Cut and Ground Clean

Pre-Weld Cleaning: Wire Brush

Interpass Cleaning: Slag Pick and Wire Brush

Geometry and Fit-Up:



Type Restraint: None

Electrode Shape or Tip Data: .071"(0.18cm) dia. tube and 0.070"(0.18cm) dia. tip.

FIXED PARAMETERS	Initial	As Varied
Process	SMA	GMA
Manual, Auto, etc	Manual	Semi-Automatic
Polarity	DCRP	DCRP
Position	Flat	Flat
Base Material	HY-150	to Same
Source	U.S. Steel Corp.	
Heat Treatment	Quenched&Tempered	
Thickness, Size	6"x6"x24"(15.24cm x 15.24cm x 60.9cm)	
Filler Wire	McKay E-14018 AW	Airco AX-140
Diameter	1/8"(0.32cm)&3/16(0.47cm)	0.062"(0.16cm)
Producer & Heat	#422W2201	#1P1338
Lot & Spool No.	--	--
Torch	--	Linde ST-5
Gas or Flux	--	Argon/2% Oxygen
Backing Material	--	--
Backing Gas	--	--
Heat Input Limits (Max)	35KJ/in 13.7KJ/cm	55KJ/in 21.6KJ/cm
Preheat	250°F(121°C)	
Postheat	Cont.200°F (93°C)Min.-held 16 hours	after finish.
Interpass	300°F(148°C)Max.	
Welding Head	--	--
Wire Feeders	--	Linde AWM-11-S
Meters & Locations	EB #300R	EB #400R
Recorders	--	--
Power Supply	P & H - Drooping	Vickers - C.P.

Special or Non-st'd Devices: Automatic preheat and post heat control.

Mat'l Handling & Storage:
a) Bare wire covered with plastic cover overnight.
b) Weldment @ 300°F(148°C) overnight.

Cognizant Engineer: P. Schmidt

Weldor: W. Graham and R. Root, Jr.

REQUIRED SAMPLES (Take and Identify)

	Wire-Start of Joint
X	Wire-Start of Spool
	Wire-Start of Shift
	Other:

REQUIRED INSPECTION

X	Fit-Up,	[X]	Vis	[ ]	LP
X	Root,	[ ]	LP	[X]	MP
X	Back-side	[ ]	LP	[X]	MP
X	Final,	[X]	LP	[X]	MP
		[X]	RT	[ ]	UT
	Intermediate	[ ]	LP	[ ]	MP

APPLICABLE SPECS.

Welding Procedure:

Base Material: MIL-S-24371 (SHIPS)

Weld Filler Wire: MI-30-CE/1,Incl.Appx.A

Radiographic Inspector: NAVSHIPS 250-1500-1

Ultrasonic Inspection:

TABLE IX (Cont'd) - Welding Parameters for Weldments PD-4833, PD-4834 and PD-4835

---DEPOSITION SEQUENCE AND FOLLOWING DATA FOR EACH WELD BEAD---

Pass No.	Arc Amp.	Arc Volts	Travel* ipm (cm/pm)	Wire ipm (cm/pm)	Pulsed-Arc Peak	Pulsed-Arc Bkgd.	Cup Size	Total cfh (cmh)	Cup/Work inches (cm)	Tip/Work inches (cm)	Weld Start Temp. °F (°C)	Comments (Repairs, etc.)
Root	120/130	23	4-5 10.2-12.7	--	--	--	--	--	--	--	250 121	1/8" (0.32cm) SMA
2-18	230	21	6-8 15.2-20.3	--	--	--	--	--	--	--	" "	3/16" (0.47cm) SMA
19-29	315/325	25/26	12-14 30.4-35.6	250 635	--	--	#8	45 1.27	1/2 1.27	5/8 1.59	260 127	1/16" (0.16cm) SMA
30-42	355-365	"	" "	264 670	--	--	#8	" "	" "	" "	210 98	" " "
43-111	"	"	" "	" "	--	--	#10	" "	" "	" "	" "	" " "
112-241	290/310	"	13-16 33-40.6	180 457	--	--	#10	" "	" "	" "	" "	" " "

*Typical

TABLE X - Summary of HY-150 Base Metal Tensile Properties - U.S.S. Heat #5P3947

U.S. Steel Test Results:		0.2% Offset Yield Strength PSI (MPa)	Tensile Strength PSI (MPa)	% Elong in 2" (5.1 cm)	% Red. Of Area
Plate F-4602 (Transverse)					
	End #1	138,620(955)	154,410(1063)	17.0	52.6
	End #2	144,540(997)	155,400(1072)	17.0	47.0
Plate F-4603 (Transverse)					
	End #1	140,470(970)	155,160(1070)	17.0	52.9
	End #2	139,870(964)	152,980(1051)	16.0	44.9

E.B. Div. Test Results:

Specimen Number	Master Plate Orientation	0.2% Offset Y.S., PSI(MPa)	Tensile Strength, PSI(MPa)	Reduction of Area, %	Elongation %in2"(5.1cm)
PD-12BM-B	F-4602 (Longitudinal)	133,500 (925)	150,000 (1035)	50.8	15.0
PD-12BM-G	F-4602 (Transverse)	133,500 (925)	148,500 (1022)	44.0	13.0
PD-12BM-A	F-4602 (S.Transverse)	137,500 (947)	144,000 (994)	11.5	4.0
PD-13BM-B	F-4603 (Longitudinal)	140,000 (966)	154,500 (1064)	53.0	15.0
PD-13BM-G	F-4603 (Transverse)	139,000 (960)	154,000 (1061)	41.5	13.0
PD-13BM-A	F-4603 (S.Transverse)	142,500 (984)	152,000 (1049)	9.2	4.0

Note: E.B. Div. results are from one 0.505" (1.28cm) round tensile specimen. Longitudinal and transverse specimens are from plate midthickness.

TABLE XI - Charpy V-Notch Impact Data as Reported By U.S. Steel for Master Plates F-4602 and F-4603

Plate Number	Specimen Orientation	Test Temperature °F	Test Temperature °C	Absorbed Energy, Ft.-Lbs. (Joules)
Plate F-4602	End #1, Trans.	0	-17	48, 50, 52-Avg.50 (65, 68, 71-Avg.68)
	End #1, Trans.	72	22	50, 54, 52-Avg.52 (68, 73, 71-Avg.71)
	End #2, Long.	0	-17	60, 55, 58-Avg.58 (82, 75, 79-Avg.79)
	End #2, Long.	72	22	62, 60, 62-Avg.61 (84, 82, 84-Avg.83)
Plate F-4603	End #1, Trans.	0	-17	53, 53, 57-Avg.54 (72, 72, 77 Avg.73)
	End #1, Trans.	72	22	58, 61, 66-Avg.62 (79, 83, 90-Avg.84)
	End #2, Long.	0	-17	60, 62, 55-Avg.59 (82, 84, 75-Avg.80)
	End #2, Long.	72	22	71, 70, 73-Avg.71 (96, 95, 99-Avg.96)
MIL-S-24371	Long. or Trans.	0°F(-17°C)& room temp. 70°F Min. (21°C)		60 (82) Avg. of 3 Tests (1) (2)

Notes: (1) No single test shall be more than 5 ft.-lbs. (6.8J) below the average.

(2) The average ft.-lbs. at room temperature 70°F (21°C) min. shall not exceed by more than 10 ft.-lbs. (13.6J) the avg. at 0°F (-17°C).

TABLE XII - CVN Impact Energy Vs. Temperature Data for Master Plates F-4602 and F-4603 - E.B. Div. Test Results

Plate Number	Specimen Orientation	Test Temperature °F	Test Temperature °C	CVN Impact Strength Ft.-Lbs.	CVN Impact Strength Joules
F-4602	Longitudinal	+212	(100)	86,88	(117,120)
		175	(79.5)	87,88	(118,120)
		125	(51.5)	77,80	(105,109)
		76	(24.4)	72,77	(98,105)
		30	(-1.1)	75,78	(102,106)
		0	(-17.8)	57,65	(78,88)
		-60	(-51)	39,39	(53,53)
		-100	(-73)	31,34	(42,46)
		-150	(-101)	17,23	(23,31)
		-170	(-112)	20,30	(27,41)
		-300	(-184)	7,6	(9,8)
F-4602	Transverse	+212	(100)	66,67	(90,91)
		175	(79.5)	61,64	(83,87)
		125	(51.5)	59,62	(80,84)
		76	(24.4)	59,66	(80,90)
		30	(-1.1)	56,69	(76,94)
		0	(-17.8)	39,47	(53,64)
		-60	(-51)	32,36	(44,49)
		-100	(-73)	21,32	(28,44)
		-150	(-101)	17,20	(23,27)
		-170	(-112)	10,23	(13,31)
		-300	(-184)	6,6	(8,8)
F-4603	Transverse	+212	(100)	68,70	(92,95)
		175	(79.5)	60,64	(82,87)
		125	(51.5)	64,66	(87,90)
		76	(24.4)	64,67	(87,91)
		30	(-1.1)	56,59	(76,80)
		0	(-17.8)	48,56	(65,76)
		-60	(-51)	41,41	(56,56)
		-100	(-73)	25,31	(34,42)
		-150	(-101)	19,29	(26,39)
		-170	(-112)	23,28	(31,38)
		-300	(184)	6,6	(8,8)

TABLE XIII -- HY-150 BASE METAL FRACTURE TOUGHNESS TEST DATA

Specimen Type: Notched Bend

Loading Method: Four Point Bending - constant moment at notched area.

Major Span - 96" (244cm)

Minor Span - 24" (62.2cm)

	SPECIMEN IDENTIFICATION	
	PD-2BMK (Plate F-4602)	PD-3BMK (Plate F-4603)
Thickness (B)	6.0" (15.24 cm)	6.15" (15.62 cm)
Depth (W)	24.5" (62.2 cm)	25.01" (63.5 cm)
Fatigue Precracking Parameters:		
K_f (Max.) for Crack Completion	43.6 Ksi $\sqrt{in.}$ (48 MPa · m 1/2)	44.3 Ksi $\sqrt{in.}$ (48.8 MPa · m 1/2)
ΔK_f Final at Crack Completion	39.5 Ksi $\sqrt{in.}$ (43.5 MPa · m 1/2)	37.7 Ksi $\sqrt{in.}$ (41.5 MPa · m 1/2)
Cycles at ΔK_f (Final) for Crack Completion	153,700	152,700
Crack Length:		
Surface (1)	14.05" (35.7 cm)	12.72" (32.3 cm)
1/4 Point	13.73" (34.9 cm)	13.42" (34.1 cm)
Center	14.05" (35.7 cm)	13.58" (34.5 cm)
3/4 Point	13.26" (33.7 cm)	13.42" (34.1 cm)
Surface (2)	11.40" (29 cm)	12.41" (31.5 cm)
Test Temperature	65°F (18.3°C)	65°F (18.3°C)
Relative Humidity	Not Recorded	Not Recorded
Loading Rate, KI/Time	20 Ksi $\sqrt{in.}$/min. (22 MPa · m 1/2)	20 Ksi $\sqrt{in.}$/min. (22 MPa · m 1/2)

2

TABLE XIII -- HY-150 BASE METAL FRACTURE TOUGHNESS TEST DATA (Continued)

	PD-2BMK (Plate F-4602)	PD-3BMK (Plate F-4603)
Crack Length (Continued):		
Fracture Appearance	40% Shear	40% Shear
Yield Strength	133,500 Psi (922 MPa)	140,000 Psi (966 MPa)
Stress Intensity Factor K_Q	214.5 Ksi $\sqrt{in.}$ (236 MPa · m 1/2)	270 Ksi $\sqrt{in.}$ (297 MPa · m 1/2)

TABLE XIV - All-Weld-Metal Tensile and Charpy Impact Test Data - SMA Welds in Restrained 2-Inch (5.1cm) HY-80 Base Plate

Tensile Properties

Specimen Number	Location (Fig.10)	0.2% Offset Y.S., Psi (MPa)	Tensile Strength. Psi (MPa)	% Reduction of Area	% Elongation in 2" (5.1cm)
PD-4836-T1	T	148,000 (1020)	152,000 (1048)	61.0	17.0
PD-4836-T3	T	150,500 (1038)	155,300 (1072)	58.0	14.0
PD-4836-T2	B	142,500 (983)	150,000 (1035)	63.0	17.0
PD-4836-T4	B	143,300 (990)	148,500 (1025)	61.5	15.0

Charpy V-Notch Impact Properties

Specimen Number	Location (Fig.10)	CVN Impact Values, Ft.-Lbs. (Joules) 0°F (-17°C)	32°F (0°C)	72°F (22°C)
PD-4836-C1	T	71 (96)		
-C2	T	76 (103)		
-C3	T		83 (113)	
-C4	T		83 (113)	
-C5	T			89 (121)
-C6	T			93 (126)
-C7	B	86 (117)		
-C8	B	83 (113)		
-C9	B		92 (125)	
-C10	B		97 (132)	
-C11	B			89 (121)
-C12	B			95 (129)

TABLE XV - All Weld Metal Tensile Data-GMA Welds on Restrained 4-Inch (10.2 cm) HY-80 Base Plate

Specimen Number	Location (Fig.11)	0.2% Offset Y.S., Psi (Mpa)	Tensile Strength, Psi (MPa)	% Reduction of Area	% Elongation in 2" (5.1cm)
PD-4837-T1	A	140,000 (966)	144,500 (995)	60.3	17.0
PD-4837-T5	A	135,000 (935)	144,500 (995)	61.6	18.0
PD-4837-T2	B	145,000 (1000)	151,000 (1040)	59.1	17.0
PD-4837-T6	B	146,000 (1008)	151,250 (1042)	46.9	13.0
PD-4837-T3	C	137,500 (948)	142,000 (980)	63.0	18.0
PD-4837-T7	C	142,000 (980)	145,750 (1004)	60.1	17.0
PD-4837-T4	D	139,000 (960)	144,000 (995)	62.8	18.0
PD-4837-T8	D	137.000 (946)	143,500 (990)	59.0	18.0

TABLE XVI - Charpy V-Notch Impact Data - GMA Welds in Restrained 4" (10.2cm) HY-80 Base Plate

Specimen Number	Location (Fig. 11)	CVN Impact Values, Ft.-Lbs. (Joules) 0°F (-17°C)	32°F (0°C)	72°F (22°C)
PD-4837-A1	A	--	--	--
-A2	A			72 (98)
-A3	A		58 (79)	
-A4	A		61 (83)	
-A5	A	53 (72)		
-A6	A	55 (75)		
-B1	B			64 (87)
-B2	B			60 (82)
-B3	B		53 (72)	
-B4	B		53 (72)	
-B5	B	56 (76)		
-B6	B	55 (75)		
-C1	C			67 (91)
-C2	C			63 (86)
-C3	C		61 (83)	
-C4	C		58 (79)	
-C5	C	56 (76)		
-C6	C	48 (65)		
-D1	D			68 (93)
-D2	D			68 (93)
-D3	D		55 (75)	
-D4	D		55 (75)	
-D5	D	53 (72)		
-D6	D	52 (71)		

TABLE XVII -- SMA WELDMENT TENSILE PROPERTIES (SET SMA-1)

Transverse Tensile Properties: 0.505-inch (1.28cm) specimens with reduced section including portions of weld metal, HAZ and base metal

Specimen Number	Specimen Location	U.T.S., Ksi (MPa)	0.2%Y.S., Ksi (MPa)	Elong., % in 2" (5.1 cm)	R.A. %	Failure Location
PD-4827-TT1	Top, Near Surface	144 (995)	137 (947)	15.0	64	Broke in Weld
-TT2	Near Mid-Thickness, Top 1/2	147 (1015)	141 (972)	14.0	63	" " "
-TT3	Mid-Thickness	150 (1035)	136 (940)	16.0	62	" " "
-TT4	Near Mid-Thickness	148 (1020)	133 (920)	16.0	62	" " "
-TT5	Bottom, Near Surface	146 (1008)	140 (966)	14.0	58	" " "
-TT6*	Near Mid-Thickness, Top 1/2	148 (1020)	143 (986)	15.0	65	" " "

*This specimen was from same layer as -TT2, only in opposite sidewall area.

Longitudinal All-Weld Tensile Properties: 0.505-inch (1.28cm) specimens taken at various depths on weld centerline

Specimen Number	Specimen Location	U.T.S., Ksi (MPa)	0.2% Y.S., Ksi (Mpa)	Elong., % in 2" (5.1cm)	R.A. %	Preheat °F (°C)	Avg. Heat Input, Kj/in. (Kj/cm)
PD-4825-T1	Top, Near Surface	141 (972)	134 (925)	18.0	59	300 (149)	27 (10.6)
-T2	Near Mid-Thickness	145 (1000)	138 (953)	17.0	66	275 (125)	24 (9.45)
-T3	Mid-Thickness	150 (1035)	143 (986)	14.0	58	200 (93)	42 (16.5)
-T4	Near Mid-Thickness, Bottom 1/2	146 (1008)	139 (960)	16.0	65	275 (125)	28 (11.0)
-T5	Bottom, Near Surface	142 (980)	135 (932)	18.0	64	300 (149)	28 (11.0)

TABLE XVIII -- 6" (15.24cm) HY-150 SMA Weldment Charpy Impact Properties

Transverse (HAZ) Charpy Test Results: (CVN specimens oriented transverse to weld centerline, with notched surface parallel to top and bottom surfaces of weldment)

Specimen Number	Specimen Location	Temperature °F	(°C)	CVN Impact, Ft.-Lbs.	(Joules)	
PD-4825-C1	Near Top Surface	72	(22)	72	(98)	
-C3	1/4 Thickness	72	(22)	77	(105)	
-C7	Mid-Thickness	72	(22)	78	(106)	Avg.@72°F(-22°C)= 75 (102)
-C4	3/4 Thickness	72	(22)	82	(111)	
-C6	Near Bottom Surface	72	(22)	68	(92)	
-C2	1/8 Thickness	0	(-17)	59	(80)	
-C5	7/8 Thickness	0	(-17)	67	(91)	

Longitudinal All-Weld Charpy Test Results: (CVN specimens oriented longitudinal to weld with notch perpendicular to top and bottom surfaces of weldment, on weld centerline)

Specimen Number	Specimen Location	Temperature °F	(°C)	CVN Impact, Ft.-Lbs.	(Joules)	
PD-4827-C1	Near Top Surface	72	(22)	107	(146)	
-C3	1/4 Thickness	72	(22)	72	(98)	
-C7	Mid-Thickness	72	(22)	95	(129)	
-C4	3/4 Thickness	72	(22)	97	(132)	Avg.@72°F(-22°C)= 98 (133)
-C6	Near Bottom Surface	72	(22)	99	(134)	Avg.@0°F(-17°C)= 91 (124)
-C2	1/8 Thickness	0	(-17)	92	(125)	
-C5	7/8 Thickness	0	(-17)	90	(122)	

TABLE XIX -- GMA WELDMENT PD-4825, HEAT INPUT DATA FOR ALL-WELD TENSILE SPECIMENS

Specimen -T1		Speci en -T2		Specimen -T3		Specimen -T4		Specimen -T5	
Weld Beads Tested	Heat Input, Kj/in(cm)	Weld Beads Tested	Heat Input, Kj/in(cm)	Weld Beads Tested	Heat Input, Kj/in(cm)	Weld Beads Tested	Heat Input, Kj/in(cm)	Weld Beads Tested	Heat Input, Kj/in(cm)
# 89	27(10.6)	#18	25(9.8)	#46*	40(15.7)	#61*	26(10.2)	#141*	27(10.6)
96	27 "	19	25(9.8)	47*	40(15.7)	62*	26(10.2)	142*	27 "
99	27 "	22	24(9.4)	48*	41(16.1)	67*	28(11)	150*	27 "
107	27 "	23	24(9.4)	49*	41(16.1)	69*	28(11)	151*	27 "
108	27 "	24	24(9.4)	50*	45(17.7)	71*	28(11)	152*	27 "
109	27 "	28	23(9.0)	51*	45(17.7)	72*	29(11.4)	159*	27 "
117	27 "	29	23(9.0)	52*	44(17.3)	76*	29(11.4)	161*	27 "
118	27 "		—		—		—	171*	27 "
Avg.	27(10.6)	Avg.	24(9.4)	Avg.	42(16.5)	Avg.	28(10.2)	Avg.	27(10.6)

*Backside of Weld Joint

TABLE XX -- RESULTS OF R_C HARDNESS TRAVERSE, WELDMENT PD-4827
(See Figure 30)

Loc. No.	Rc No.	Zone	Loc. No.	Rc No.	Zone	Loc. No.	Rc No.	Zone	Loc. No.	Rc No.	Zone
1.	36		26.	33		51.	37		76.	34	
2.	37		27.	30		52.	36		77.	35	
3.	36		28.	34		53.	36		78.	37	
4.	37		29.	33		54.	36		79.	38	
5.	37	BM	30.	32		55.	36		80.	35	HAZ
6.	36		31.	35		56.	37		81.	37	
7.	35		32.	35	WELD	57.	37		82.	36	
8.	34	HAZ	33.	32		58.	37		83.	36	
9.	38		34.	35		59.	37		84.	36	
10.	37		35.	34		60.	37		85.	35	
11.	34		36.	35		61.	36		86.	35	
12.	35		37.	34		62.	36		87.	36	BM
13.	36		38.	35		63.	36		88.	35	
14.	33		39.	37		64.	37		89.	36	
15.	33		40.	35		65.	34		90.	35	
16.	33	WELD	41.	36		66.	34		91.	35	
17.	31		42.	36		67.	32		92.	36	
18.	32		43.	37		68.	33		93.	38	
19.	32		44.	36		69.	32	WELD	94.	38	
20.	30		45.	37	BM	70.	32		95.	36	
21.	33		46.	37		71.	35		96.	34	
22.	34		47.	37		72.	32		97.	34	WELD
23.	31		48.	37		73.	33		98.	34	
24.	30		49.	36		74.	36		99.	34	
25.	33		50.	37		75.	35		100.	33	

TABLE XX (Continued)

Loc. No.	Rc No.	Zone	Loc. No.	Rc No.	Zone	Loc. No.	Rc No.	Zone	Loc. No.	Rc No.	Zone
101.	36		126.	36		151.	33		176.	35	
102.	34		127.	36		152.	32		177.	35	
103.	36		128.	36		153.	34		178.	35	
104.	37		129.	36		154.	35		179.	37	
105.	34		130.	35		155.	37		180.	38	
106.	32	WELD	131.	35		156.	35	HAZ	181.	37	
107.	33		132.	36		157.	35		182.	35	
108.	35		133.	36	BM	158.	37		183.	35	
109.	36		134.	36		159.	36		184.	35	
110.	37		135.	35		160.	36	BM	185.	35	BM
111.	41	HAZ	136.	36		161.	36		186.	35	
112.	36		137.	34		162.	36		187.	35	
113.	37		138.	35		163.	35		188.	35	HAZ
114.	36		139.	34		164.	33		189.	35	
115.	36		140.	36		165.	33		190.	38	
116.	36		141.	38	HAZ	166.	32		191.	34	
117.	36		142.	36		167.	33		192.	38	
118.	NR	BM	143.	35		168.	34		193.	37	WELD
119.	35		144.	34		169.	32		194.	37	
120.	34		145.	35		170.	33	WELD	195.	36	
121.	35		146.	33		171.	39		196.	38	HAZ
122.	36		147.	34	WELD	172.	37		197.	35	
123.	36		148.	32		173.	39		198.	35	
124.	36		149.	36		174.	37		199.	35	BM
125.	36		150.	35		175.	38		200.	36	

*NR - Not Recorded

TABLE XX (Continued)

Loc. No.	Rc No.	Zone	Loc. No.	Rc No.	Zone	Loc. No.	Rc No.	Zone	Loc. No.	Rc No.	Zone
201.	35		226.	34		251.	37		276.	38	
202.	35		227.	35		252.	37		277.	39	
203.	34		228.	37		253.	38		278.	38	
204.	34		229.	37		254.	38		279.	39	
205.	36		230.	37		255.	36		280.	38	
206.	35		231.	35		256.	37		281.	39	WELD
207.	35		232.	38		257.	36		282.	39	
208.	35		233.	37		258.	37		283.	40	
209.	34		234.	36		259.	37		284.	38	
210.	35		235.	39		260.	35		285.	39	
211.	34	BM	236.	33		261.	35		286.	39	
212.	35		237.	38		262.	36	WELD	287.	38	
213.	34		238.	35	WELD	263.	37		288.	34	
214.	36		239.	39		264.	37		289.	35	
215.	34		240.	39		265.	35		290.	34	
216.	36		241.	37		266.	38		291.	33	BM
217.	34		242.	37		267.	37		292.	32	
218.	37		243.	40		268.	37		293.	33	
219.	35		244.	40		269.	38		294.	34	HAZ
220.	35		245.	39		270.	36		295.	40	
221.	34		246.	41		271.	36		296.	36	
222.	34		247.	38		272.	38		297.	35	
223.	34		248.	39		273.	38		298.	33	WELD
224.	33		249.	36		274.	38		299.	33	
225.	34		250.	36		275.	38		300.	34	

TABLE XX (Continued)

Loc. No.	Rc No.	Zone	Loc. No.	Rc No.	Zone	Loc. No.	Rc No.	Zone	Loc. No.	Rc No.	Zone
301.	34		326.	35		351.	35		376.	33	
302.	33		327.	33		352.	36		377.	33	
303.	33		328.	34		353.	35		378.	31	
304.	34		329.	33		354.	37		379.	33	
305.	35		330.	33		355.	39		380.	32	
306.	37	WELD	331.	33		356.	34	HAZ	381.	33	
307.	37		332.	32	BM	357.	33		382.	34	
308.	36		333.	34		358.	34		383.	34	
309.	37		334.	34		359.	35		384.	34	
310.	36		335.	34		360.	34		385.	37	
311.	38		336.	34		361.	33		386.	36	HAZ
312.	35	HAZ	337.	34		362.	33		387.	37	
313.	34		338.	34		363.	35	BM	388.	36	
314.	34		339.	34		364.	35		389.	36	
315.	34		340.	34		365.	34		390.	36	
316.	34		341.	34		366.	34		391.	36	BM
317.	35		342.	37		367.	36		392.	37	
318.	35		343.	35		368.	36	HAZ	393.	33	
319.	34	BM	344.	34		369.	36		394.	35	
320.	35		345.	33		370.	33		395.	35	
321.	35		346.	33	WELD	371.	35		396.	35	
322.	33		347.	34		372.	32	WELD	397.	35	
323.	33		348.	36		373.	33		398.	36	HAZ
324.	34		349.	36		374.	31		399.	34	
325.	34		350.	35		375.	33		400.	36	WELD

TABLE XX (Continued)

Loc. No.	Rc No.	Zone	Loc. No.	Rc No.	Zone	Loc. No.	Rc No.	Zone	Loc. No.	Rc No.	Zone
401.	37		426.	34		451.	36		476.	35	
402.	32		427.	38		452.	37		477.	35	
403.	33		428.	35		453.	36		478.	34	
404.	32		429.	36		454.	36		479.	35	
405.	29		430.	34		455.	36		480.	35	
406.	30		431.	37	HAZ	456.	36		481.	36	
407.	30		432.	37		457.	36		482.	36	
408.	31		433.	37		458.	35		483.	35	BM
409.	31		434.	36		459.	37		484.	36	
410.	30	WELD	435.	37		460.	35		485.	36	
411.	33		436.	37		461.	36		486.	36	
412.	31		437.	37		462.	36	BM	487.	37	
413.	31		438.	37		463.	34		488.	37	
414.	29		439.	37		464.	37		489.	37	
415.	30		440.	39	BM	465.	34				
416.	28		441.	37		466.	34				
417.	31		442.	37		467.	35				
418.	33		443.	37		468.	36				
419.	30		444.	36		469.	34				
420.	29		445.			470.	35				
421.	30		446.	36		471.	35				
422.	30		447.	37		472.	34				
423.	30		448.	36		473.	34				
424.	30		449.	37		474.	34				
425.	31		450.	36		475.	36				

TABLE XXI -- GMA WELDMENT TENSILE PROPERTIES (SET GMA-1)

Transverse Tensile Properties: 0.505-inch (1.28cm) specimens with reduced section including portions of weld metal, HAZ and base metal

Specimen Number	Specimen Location	U.T.S., Ksi (MPa)	0.2%Y.S., Ksi (MPa)	Elong., % in 2" (5.1 cm)	R.A. %	Failure Location
PD-4831-TT1	Top, Near Surface	144 (995)	137 (946)	16.0	61	Broke in Weld
-TT2	Near Mid-Thickness, Top 1/2	155 (1070)	143 (986)	15.0	57	Broke in Base Plate
-TT3	Mid-Thickness	152 (1050)	137 (946)	16.0	60	" " " "
-TT4	Near Mid-Thickness, Bottom 1/2	151 (1040)	138 (953)	16.0	59	" " " "
-TT5	Bottom, Near Surface	152 (1050)	141 (973)	15.0	60	Broke in Weld
-TT6*	Near Mid-Thickness, Top 1/2	152 (1050)	13 (960)	16.0	62	Broke in Base Plate

*This specimen was from high heat input area of same layer as -TT2, in opposite sidewall area.

Longitudinal All-Weld Tensile Properties: 0.505-inch (1.28cm) specimens taken at various depths on weld centerline

Specimen Number	Specimen Location	U.T.S., Ksi (MPa)	0.2%Y.S., Ksi (MPa)	Elong., %in2" (5.1cm)	R.A. %	Preheat °F (°C)	Avg. Heat Input, Kj/in. (Kj/cm)
PD-4830-T1	Top, Near Surface	143 (986)	137 (946)	18.0	61	300 (154)	29 (11.4)
-T2	Near Mid-Thickness, Top 1/2	154 (1062)	147 (1015)	16.0	59	250 (121)	36 (14.2)
-T3	Mid Thickness	159 (1100)	150 (1030)	16.0	58	225 (107)	38 (14.9)
-T4	Near Mid-Thickness, Bottom 1/2	154 (1062)	147 (1015)	16.0	64	250 (121)	34 (13.4)
-T5	Bottom, Near Surface	147 (1015)	141 (972)	18.0	62	300 (154)	27 (10.6)

TABLE XXII -- GMA WELDMENT CHARPY IMPACT PROPERTIES (SET GMA-2)

Transverse (HAZ) Charpy Test Results: (CVN specimen oriented transverse to weld centerline, with notched surface parallel to top and bottom surfaces of weldment)

Specimen Number	Specimen Location	Temperature °F	(°C)	CVN Impact, Ft.-Lbs.	(Joules)	
PD-4830-C1	Near Top Surface	72	(22)	76	(103)	
-C3	1/4 Thickness	72	(22)	75	(102)	
-C7	Mid-Thickness	72	(22)	90	(122)	
-C4	3/4 Thickness	72	(22)	83	(113)	Avg.@72°F(22°C)= 80(109)
-C6	Near Bottom Surface	72	(22)	77	(105)	Avg.@0°F(-17°C)= 71(97)
-C2	1/8 Thickness	0	(-17)	63	(85)	
-C5	7/8 Thickness	0	(-17)	79	(107)	

Longitudinal All-Weld Charpy Test Results: (CVN specimens oriented longitudinal to weld with notch perpendicular to top and bottom surfaces of weldment, on weld centerline)

Specimen Number	Specimen Location	Temperature °F	(°C)	CVN Impact, Ft.-Lbs.	(Joules)	
PD-4831-C1	Near Top Surface	72	(22)	61	(83)	
-C3	1/4 Thickness	72	(22)	58	(79)	
-C7	Mid-Thickness	72	(22)	52	(71)	
-C4	3/4 Thickness	72	(22)	56	(76)	Avg.@72°F(22°C)= 58(79)
-C6	Near Bottom Surface	72	(22)	64	(87)	Avg.@0°F(-17°C)= 54(73)
-C2	1/8 Thickness	0	(-17)	62	(84)	
-C5	7/8 Thickness	0	(-17)	56	(76)	

TABLE XXIII -- GMA WELDMENT PD-4830, HEAT INPUT DATA FOR ALL-WELD TENSILE SPECIMENS

Specimen -T1		Specimen -T2		Specimen -T3		Specimen -T4		Specimen -T5	
Weld Beads Tested	Heat Input, Kj/in(cm)	Weld Beads Tested	Heat Input, Kj/in(cm)	Weld Beads Tested	Heat Input, Kj/in(cm)	Weld Beads Tested	Heat Input, Kj/in(cm)	Weld Beads Tested	Heat Input, Kj/in(cm)
# 92	25(9.8)	#12	40(15.7)	#24	40(15.7)	#36	34(13.4)	#144	27(10.6)
93	28(11)	15	43(16.9)	25	43(16.9)	39	34 "	145	28(11)
215	30(11.8)	18	37(14.6)	26	37(14.6)	40	34 "	152	26(10.2)
216	30 "	19	43(16.9)	27	36(14.2)	43	34 "	153	27(10.6)
217	30 "	56	31(12.2)	28	39(15.3)	47	34 "	154	28(11)
225	30 "	57	30(11.8)	30	36(14.2)	48	34 "	161	26(10.2)
226	30 "	62	27(10.6)					162	25(9.8)
227	30 "							163	26(10.2)
238	30 "							171	27(10.6)
239	30 "							172	27(10.6)
Avg.	29(11.4)	Avg.	36(14.2)	Avg.	38(14.9)	Avg.	34(13.4)	Avg.	27(10.6)

TABLE XXIV -- RESULTS OF R_C HARDNESS TRAVERSE, WELDMENTS PD-4831
(See Figure 34)

Loc. No.	Rc No.	Zone	Loc. No.	Rc No.	Zone	Loc. No.	Rc No.	Zone	Loc. No.	Rc No.	Zone
1.	37		26.	32		51.	32		76.	39	
2.	36	BM	27.	30		52.	32		77.	37	HAZ
3.	36		28.	30		53.	34		78.	38	
4.	36	HAZ	29.	30		54.	35		79.	36	
5.	38		30.	30		55.	38		80.	35	
6.	38		31.	30		56.	35	HAZ	81.	36	
7.	36		32.	32		57.	37		82.	36	
8.	35		33.	32		58.	35		83.	36	
9.	35		34.	36		59.	36		84.	36	
10.	33		35.	39		60.	36	BM	85.	39	
11.	35		36.	36	HAZ	61.	35		86.	38	BM
12.	33		37.	36		62.	37		87.	37	
13.	35		38.	37		63.	37		88.	37	
14.	36		39.	36		64.	36	HAZ	89.	37	
15.	35		40.	36	BM	65.	37		90.	38	
16.	35	WELD	41.	37		66.	37		91.	38	
17.	30		42.	36		67.	36		92.	37	
18.	35		43.	37		68.	38		93.	37	
19.	32		44.	37	HAZ	69.	33		94.	35	
20.	32		45.	38		70.	37	WELD	95.	36	
21.	33		46.	36		71.	37		96.	36	
22.	32		47.	34		72.	37		97.	37	HAZ
23.	31		48.	32	WELD	73.	37		98.	40	
24.	29		49.	32		74.	38		99.	39	WELD
25.	30		50.	32		75.	36		100.	38	

TABLE XXIV (Continued)

Loc. No.	Rc No.	Zone	Loc. No.	Rc No.	Zone	Loc. No.	Rc No.	Zone	Loc. No.	Rc No.	Zone
101.	37		126.	38		151.	38		176.	35	
102.	37		127.	37		152.	38		177.	35	
103.	38		128.	40		153.	37		178.	34	
104.	38		129.	41		154.	41		179.	34	
105.	36		130.	38		155.	39		180.	34	
106.	35		131.	39		156.	40		181.	35	
107.	33		132.	40		157.	42		182.	35	
108.	34	WELD	133.	40		158.	39	WELD	183.	36	
109.	33		134.	38		159.	39		184.	35	
110.	37		135.	41		160.	39		185.	34	
111.	37		136.	38		161.	35		186.	34	
112.	36		137.	38		162.	40		187.	34	HAZ
113.	36		138.	38		163.	35		188.	40	
114.	40		139.	35	WELD	164.	40		189.	39	
115.	36		140.	36		165.	36		190.	41	
116.	36		141.	39		166.	34		191.	39	
117.	35	HAZ	142.	38		167.	33		192.	38	
118.	35		143.	41		168.	34		193.	37	WELD
119.	35		144.	38		169.	34		194.	37	
120.	35		145.	39		170.	34		195.	37	
121.	44		146.	40		171.	34	BM	196.	39	
122.	34	WELD	147.	41		172.	35		197.	34	HAZ
123.	39		148.	39		173.	34		198.	36	
124.	37		149.	39		174.	34		199.	33	BM
125.	39		150.	38		175.	34		200.	34	

TABLE XXIV (Continued)

Loc. No.	Rc No.	Zone	Loc. No.	Rc No.	Zone	Loc. No.	Rc No.	Zone	Loc. No.	Rc No.	Zone
201.	34	BM	226.	35	HAZ	251.	35		276.	35	
202.	41		227.	37		252.	34		277.	37	
203.	39		228.	39		253.	35		278.	36	
204.	38		229.	38		254.	35		279.	36	
205.	37		230.	38		255.	35		280.	39	WELD
206.	38		231.	39		256.	35	BM	281.	41	
207.	37		232.	36		257.	35		282.	40	
208.	38		233.	37		258.	35		283.	35	
209.	41	WELD	234.	37	WELD	259.	34		284.	35	
210.	40		235.	41		260.	35		285.	34	
211.	39		236.	41		261.	33		286.	34	
212.	37		237.	38		262.	30		287.	34	
213.	39		238.	37		263.	35		288.	36	
214.	39		239.	35		264.	34		289.	33	
215.	38		240.	35		265.	39	HAZ	290.	35	
216.	37		241.	35		266.	37		291.	35	
217.	41		242.	35		267.	36		292.	36	
218.	40		243.	35		268.	36		293.	36	BM
219.	36		244.	35	BM	269.	37		294.	36	
220.	39		245.	35		270.	34		295.	35	
221.	36		246.	35		271.	35	WELD	296.	36	
222.	34		247.	35		272.	34		297.	36	
223.	35	BM	248.	35		273.	34		298.	35	
224.	34		249.	35		274.	36		299.	35	
225.	34		250.	35		275.	36		300.	35	

TABLE XXIV (Continued)

Loc. No.	Rc No.	Zone	Loc. No.	Rc No.	Zone	Loc. No.	Rc No.	Zone	Loc. No.	Rc No.	Zone
301.	35	BM	326.	33		351.	33		376.	33	
302.	35		327.	34		352.	30		377.	33	
303.	34	HAZ	328.	35	WELD	353.	33		378.	33	
304.	36		329.	38		354.	36		379.	32	
305.	34		330.	34	HAZ	355.	32		380.	37	
306.	34		331.	34		356.	29		381.	37	
307.	34		332.	33		357.	33		382.	36	
308.	33		333.	30	BM	358.	36		383.	35	
309.	31		334.	35		359.	29		384.	35	
310.	32		335.	35		360.	34		385.	36	
311.	34		336.	35		361.	33		386.	35	
312.	34	WELD	337.	35		362.	31	WELD	387.	35	BM
313.	30		338.	35		363.	31		388.	35	
314.	30		339.	34	HAZ	364.	34		389.	35	
315.	31		340.	34		365.	34		390.	35	
316.	31		341.	35		366.	29		391.	34	
317.	32		342.	35		367.	32		392.	36	
318.	29		343.	35		368.	30		393.	35	
319.	33		344.	34		369.	31		394.	35	
320.	32		345.	34		370.	34		395.	35	
321.	33		346.	35		371.	34		396.	35	
322.	34		347.	33	HAZ	372.	34		397.	34	
323.	33		348.	38		373.	32		398.	34	
324.	39		349.	36		374.	37		399.	34	
325.	33		250.	34		375.	33	BM	400.	34	

TABLE XXIV (Continued)

Loc. No.	Rc No.	Zone	Loc. No.	Rc No.	Zone
401.	34		426.	35	
402.	34		427.	34	
403.	34		428.	36	
404.	35		429.	35	
405.	34		430.	36	
406.	35		431.	35	
407.	34		432.	36	
408.	36		433.	35	
409.	34		434.	36	BM
410.	34	BM	435.	36	
411.	35		436.	35	
412.	35		437.	36	
413.	34		438.	35	
414.	34		439.	36	
415.	34		440.	36	
416.	35		441.	36	
417.	34		442.	37	
418.	35		443.	36	
419.	34				
420.	34				
421.	34				
422.	36				
423.	37				
424.	35				
425.	36				

TABLE XXV -- GMA WELDMENT TENSILE PROPERTIES (SET GMA-2)

Transverse Tensile Properties: 0.505-inch (1.28 cm) specimens with reduced section including portions of weld metal, HAZ and base metal

Specimen Number	Specimen Location	U.T.S., Ksi (MPa)	0.2%Y.S., Ksi (MPa)	Elong., % in 2" (5.1cm)	R.A. %	Failure Location
PD-4824-TT1	Top, Near Surface	150 (1030)	138 (953)	15.0	59	Broke in Weld
-TT2	Near Mid-Thickness, Top 1/2	146 (1008)	138 (953)	14.0	63	" " "
-TT3	Mid-Thickness	152 (1049)	135 (930)	17.0	63	Broke in Base Plate
-TT4	Near Mid-Thickness, Bottom 1/2	147 (1015)	135 (930)	16.0	60	Broke in Weld
-TT5	Bottom, Near Surface	140 (966)	133 (917)	14.0	62	" " "
-TT6*	Near Mid-Thickness, Top 1/2	146 (1008)	137 (945)	16.0	63	" " "

*This specimen was similar to, and taken from the same layer as -TT2, only in opposite sidewall area.

Longitudinal All-Weld Tensile Properties: 0.505-inch (1.28cm) specimens taken at various depths on weld centerline

Specimen Number	Specimen Location	U.T.S., Ksi (Mpa)	0.2%Y.S., Ksi (MPa)	Elong., %in 2" (5.1cm)	R.A. %	Preheat °F (°C)	Avg. Heat Input, Kj/in. (Kj/cm)
PD-4828-T1	Top, Near Surface	138 (953)	130 (898)	19.0	63	280 (137)	26 (10.2)
-Ta**	Same Depth as -T1, but beside specimen, off ℄	144 (993)	137 (945)	18.0	62	280 (137)	26 (10.2)
-Tb**	Same Depth as -T1, but beside specimen, Off ℄	144 (993)	136 (940)	18.0	63	280 (137)	26 (10.2)

**0.252-inch (0.64cm) specimen

TABLE XXV -- GMA WELDMENT TENSILE PROPERTIES (SET GMA-2) (Continued)

Specimen Number	Specimen Location	U.T.S., Ksi (MPa)	0.2%Y.S., Ksi (MPa)	Elong., % in 2" (5.08cm)	R.A. %	Preheat °F (°C)	Avg. Heat Input, Kj/in. (Kj/cm)
PD-4828-T2	Near Mid-Thickness, Top 1/2	149 (1030)	141 (973)	18.0	63	280 (137)	29 (11.4)
-Tc**	Between -T2 and -T3, on weld ℄	144 (994)	139 (960)	14.0	63	280 (137)	39 (15.3)
-T3	Mid-Thickness	156 (1077)	148 (1020)	17.0	62	280 (137)	33 (13.0)
-T4	Near Mid-Thickness, Bottom 1/2	147 (1015)	137 (945)	17.0	61	280 (137)	27 (10.6)
-T5	Bottom, Near Surface	145 (1000)	137 (945)	17.0	60	280 (137)	26 (10.2)

TABLE XXVI -- GMA WELDMENT CHARPY IMPACT PROPERTIES (SET GMA-2)

Transverse (HAZ) Charpy Test Results: (CVN specimens oriented transverse to weld centerline, with notched surface parallel to top and bottom surfaces of weldment)

Specimen Number	Specimen Location	Temperature °F	(°C)	CVN Impact, Ft.-Lbs.	(Joules)	
PD-4828-C1	Near Top Surface	72	(22)	78	(106)	
-C3	1/4 Thickness	72	(22)	81	(110)	
-C7	Mid-Thickness	72	(22)	84	(114)	
-C4	3/4 Thickness	72	(22)	97	(132)	Avg.@72°F(22°C)= 84(114)
-C6	Near Bottom Surface	72	(22)	80	(109)	Avg.@0°F(-17°C)= 75(102)
-C2	1/8 Thickness	0	(-17)	75	(102)	
-C5	7/8 Thickness	0	(-17)	75	(102)	

Longitudinal All-Weld Charpy Test Results: (CVN specimens oriented longitudinal to weld with notch perpendicular to top and bottom surfaces of weldment, on weld centerline)

Specimen Number	Specimen Location	Temperature °F	(°C)	CVN Impact, Ft.-Lbs.	(Joules)	
PD-4824-C1	Near Top Surface	72	(22)	59	(80)	
-C3	1/4 Thickness	72	(22)	55	(75)	
-C7	Mid-Thickness	72	(22)	63	(86)	
-C4	3/4 Thickness	72	(22)	63	(86)	Avg.@72°F(22°C)= 61 (83)
-C6	Near Bottom Surface	72	(22)	67	(91)	Avg.@0°F(-17°C)= 63 (86)
-C2	1/8 Thickness	0	(-17)	63	(86)	
-C5	7/8 Thickness	0	(-17)	64	(87)	

TABLE XXVII -- GMA WELDMENT PD-4828, HEAT INPUT DATA FOR ALL-WELD TENSILE SPECIMENS

Specimen -T1		Specimen -T2		Specimen -T3		Specimen -T4		Specimen -T5	
Weld Beads Tested	Heat Input, Kj/in(cm)	Weld Beads Tested	Heat Input, Kj/in(cm)	Weld Beads Tested	Heat Input, Kj/in(cm)	Weld Beads Tested	Heat Input, Kj/in(cm)	Weld Beads Tested	Heat Input, Kj/in(cm)
#185	24(9.4)	#58	28(11)	#16*	31(12.2)	#115*	28(11)	#249*	25(9.8)
186	26(10.2)	64	29(11.4)	17*	37(14.6)	116*	26(10.2)	250*	26(10.2)
193	28(11)	65	29(11.4)	18*	36(14.2)	117*	28(11)	251*	26(10.2)
194	26(10.2)	70	30(11.8)	19*	32(12.6)	121*	26(10.2)	259*	26(10.2)
195	25(9.8)	71	31(12.2)	20*	35(13.8)	122*	27(10.6)	260*	26(10.2)
196	25(9.8)	72	30(11.8)	21*	31(12.2)	123*	26(10.2)	261*	26(10.2)
207	26(10.2)	78	29(11.4)	22*	29(11.4)	127*	26(10.2)	270*	26(10.2)
208	27(10.6)	79	30(11.8)	23*	35(13.8)	128*	28(11)	271*	26(10.2)
209	26(10.2)	80	29(11.4)	24*	31(12.2)	129*	28(11)	272*	26(10.2)
218	26(10.2)	87	28(11)			130*	26(10.2)	282*	25(9.8)
						136*	26(10.2)	283*	25(9.8)
Avg.	26(10.2)	Avg.	29(11.4)	Avg.	33(13)	Avg.	27(10.6)	Avg.	26(10.2)

*Backside of weld joint

TABLE XXVIII - RESULTS OF R_C HARDNESS TRAVERSE, WELDMENT PD-4824)
(See Figure 38)

Loc. No.	Rc No.	Zone	Loc. No.	Rc No.	Zone	Loc. No.	Rc No.	Zone	Loc. No.	Rc No.	Zone
1.	35		26.	31		51.	34		76.	33	
2.	35		27.	31		52.	34		77.	34	
3.	35		28.	32		53.	38	HAZ	78.	33	
4.	34		29.	32		54.	34		79.	35	HAZ
5.	35		30.	31		55.	34		80.	37	
6.	35	BM	31.	32		56.	33		81.	38	
7.	35		32.	32		57.	31		82.	35	
8.	35		33.	33		58.	31		83.	34	
9.	34		34.	33		59.	32		84.	35	
10.	35		35.	35		60.	31		85.	34	
11.	34		36.	35	HAZ	61.	31	WELD	86.	33	
12.	34		37.	35		62.	31		87.	33	WELD
13.	33	HAZ	38.	34		63.	32		88.	32	
14.	32		39.	35		64.	32		89.	33	
15.	32		40.	35		65.	33		90.	34	
16.	32		41.	35		66.	33		91.	36	HAZ
17.	32		42.	35		67.	34	HAZ	92.	35	
18.	31		43.	35		68.	35		93.	33	
19.	32		44.	35	BM	69.	34		94.	33	
20.	32	WELD	45.	35		70.	36		95.	33	
21.	31		46.	35		71.	36		96.	34	BM
22.	32		47.	35		72.	35	BM	97.	33	
23.	29		48.	35		73.	35		98.	33	
24.	30		49.	34		74.	32		99.	34	
25.	30		50.	36		75.	32		100.	34	

TABLE XXVIII (Continued)

Loc. No.	Rc No.		Loc. No.	Rc No.		Loc. No.	Rc No.		Loc. No.	Rc No.	
101.	34		126.	32		151.	38		176.	33	
102.	33		127.	33		152.	35		177.	33	
103.	34		128.	33		153.	36		178.	33	
104.	32		129.	33	BM	154.	33		179.	33	
105.	33		130.	34		155.	33		180.	33	
106.	33	BM	131.	33		156.	37		181.	34	
107.	33		132.	33		157.	37		182.	33	BM
108.	32		133.	39		158.	37		183.	34	
109.	32		134.	37		159.	39	HAZ	184.	33	
110.	33		135.	39		160.	37		185.	34	
111.	36	HAZ	136.	37	HAZ	161.	36		186.	34	
112.	37		137.	38		162.	39		187.	34	
113.	33		138.	40		163.	34		188.	34	
114.	34		139.	37		164.	35		189.	35	
115.	36		140.	33		165.	34		190.	36	
116.	36		141.	35		166.			191.	34	
117.	36	WELD	142.	34		167.	38		192.	34	
118.	36		143.	33		168.	40		193.	34	
119.	35		144.	36		169.	36	WELD	194.	35	
120.	34		145.	39		170.	37		195.	36	
121.	34		146.	34	WELD	171.	37		196.	40	HAZ
122.	36		147.	35		172.	35		197.	38	
123.	38		148.	34		173.	35		198.	38	WELD
124.	37	HAZ	149.	37		174.	34		199.	38	
125.	34		150.	35		175.	33		200.	35	

TABLE XXVIII (Continued)

Loc. No.	Rc No.		Loc. No.	Rc No.		Loc. No.	Rc No.		Loc. No.	Rc No.	
201.	35		226.	35		251.	36		276.	33	
202.	34		227.	32	BM	252.	34		277.	35	
203.	34		228.	35		253.	35		278.	35	
204.	33	BM	229.	35		254.	35		279.	35	HAZ
205.	34		230.	37	HAZ	255.	35		280.	35	
206.	33		231.	35		256.	35		281.	35	
207.	37		232.	33		257.	35		282.	35	
208.	36		233.	33		258.	36	BM	283.	35	
209.	38	HAZ	234.	33		259.	35		284.	34	
210.	37		235.	32	WELD	260.	35		285.	36	
211.	38		236.	33		261.	35		286.	35	
212.	36		237.	31		262.	35		287.	36	
213.	34		238.	32		263.	37		288.	36	
214.	36		239.	34		264.	34		289.	36	BM
215.	38		240.	37	HAZ	265.	36		290.	36	
216.	39		241.	34		266.	34		291.	35	
217.	36		242.	35		267.	32		292.	36	
218.	36	WELD	243.	35		268.	33	WELD	293.	35	
219.	34		244.	36		269.	33		294.	33	HAZ
220.	36		245.	36		270.	34		295.	33	
221.	36		246.	36		271.	31		296.	34	
222.	36		247.	35		272.	32		297.	35	
223.	34		248.	34		273.	31		298.	34	WELD
224.	35		249.	35		274.	33		299.	34	
225.	34		250.	35		275.	31		300.	33	

TABLE XXVIII (Continued)

Loc. No.	Rc No.	Zone	Loc. No.	Rc No.	Zone	Loc. No.	Rc No.	Zone	Loc. No.	Rc No.	Zone
301.	33		326.	36		351.	36	HAZ	376.	34	
302.	32		327.	35		352.	37		377.	33	
303.	34		328.	35	HAZ	353.	37		378.	34	
304.	34		329.	35		354.	36		379.	34	
305.	34		330.	33		355.	35		380.	34	
306.	36	WELD	331.	35		356.	35		381.	34	
307.	33		332.	35		357.	35		382.	35	
308.	36		333.	34		358.	35		383.	34	
309.	37		334.	33		359.	35		384.	35	BM
310.	37	HAZ	335.	32		360.	36		385.	34	
311.	37		336.	32		361.	36		386.	34	
312.	37		337.	31	WELD	362.	36		387.	34	
313.	37		338.	31		363.	34		388.	34	
314.	37		339.	33		364.	34		389.	34	
315.	35		340.	32		365.	34	BM	390.	33	
316.	36		341.	35		366.	34		391.	34	
317.	37	BM	342.	32		367.	35		392.	34	
318.	36		343.	34		368.	34		393.	35	
319.	36		344.	33		369.	34		394.	35	
320.	36		345.	32		370.	34		395.	34	
321.	36		346.	34		371.	34		396.	35	
322.	36		347.	35		372.	34		397.	34	
323.	36		348.	35		373.	33		398.	35	
324.	35		349.	33		374.	34		399.	34	
325.	36		250.	34		375.	34		400.	34	

TABLE XXIX -- GMA WELDMENT TENSILE PROPERTIES (SET GMA-3)

Transverse Tensile Properties: 0.505-inch (1.28cm) specimens with reduced section including portions of weld metal, HAZ and base metal

Specimen Number	Specimen Location	U.T.S., Ksi (MPa)	0.2%Y.S., Ksi (MPa)	Elong., % in 2" (5.1 cm)	R.A. %	Failure Location
PD-4834-TT1	Top, Near Surface	148 (1020)	141 (974)	15.0	55	Broke in Weld
-TT2	Near Mid-Thickness, Top 1/2	154 (1062)	141 (974)	16.0	63	Broke in Base Plate
-TT3	Mid-Thickness	150 (1035)	137 (946)	16.0	63	Broke in Base Plate
-TT4	Near Mid-Thickness, Bottom 1/2	152 (1050)	139 (960)	17.0	64	" " " "
-TT5	Bottom, Near Surface	157 (1082)	147 (1015)	18.0	63	" " " "

Longitudinal All-Weld Tensile Properties: 0.505-inch (1.28 cm) specimens taken at various depths on weld centerline

Specimen Number	Specimen Location	U.T.S., Ksi (MPa)	0.2% Y.S., Ksi (MPa)	Elong., %in2" (5.1cm)	R.A. %	Preheat °F (°C)	Avg. Heat Input, Kj/in. (Kj/cm)
PD-4833-T1	Top, Near Surface	151 (1040)	145 (1000)	16.0	64	210 (99)	39 (15.3)
-T2	Near Mid-Thickness, Top 1/2	161 (1110)	150 (1034)	15.0	60	212 (100)	51 (20)
-T3*	Mid-Thickness	164 (1131)	152 (1050)	11.0	36	264 (130)	43 (16.9)
-T4	Near Mid-Thickness, Bottom 1/2	165 (1140)	153 (1055)	14.0	57	210 (99)	47 (18.5)
-T5	Bottom, Near Surface	151 (1040)	147 (1015)	16.0	58	206 (97)	37 (14.6)

*Small defect in fracture surface

TABLE XXX -- GMA WELDMENT CHARPY IMPACT PROPERTIES (SET GMA-3)

Transverse (HAZ) Charpy Test Results: (CVN specimens oriented transverse to weld centerline, with notched surface parallel to top and bottom surfaces of weldment)

Specimen Number	Specimen Location	Temperature °F	(°C)	CVN Impact, Ft.-Lbs.	(Joules)	
PD-4833-C1	Near Top Surface	72	(22)	75	(102)	
-C3	1/4 Thickness	Test Invalid				
-C7	Mid-Thickness	72	(22)	61	(83)	
-C4	3/4 Thickness	72	(22)	80	(109)	Avg.@72°F(22°C)= 76 (103)
-C6	Near Bottom Surface	0	(-17)	74	(101)	Avg.@0°F(-17°C)= 66 (90)
-C2	1/8 Thickness	0	(-17)	55	(75)	
-C5	7/8 Thickness	0	(-17)	83	(113)	

Longitudinal All-Weld Charpy Test Results: (CVN specimens oriented longitudinal to weld with notched perpendicular to top and bottom surfaces of weldment, on weld centerline)

Specimen Number	Specimen Location	Temperature °F	(°C)	CVN Impact, Ft.-Lbs.	(Joules)	
PD-4834-C1	Near Top Surface	72	(22)	59	(80)	
-C3	1/4 Thickness	72	(22)	54	(73)	
-C7	Mid-Thickness	72	(22)	53	(72)	
-C4	3/4 Thickness	72	(22)	46	(63)	Avg.@72°F(22°C)= 54 (73)
-C6	Near Bottom Surface	72	(22)	60	(82)	Avg.@0°F(-17°C)= 47 (64)
-C2	1/8 Thickness	0	(-17)	50	(68)	
-C5	7/8 Thickness	0	(-17)	45	(61)	

TABLE XXXI -- GMA WELDMENT PD-4833, HEAT INPUT DATA FOR ALL-WELD TENSILE SPECIMENS

Specimen -T1		Specimen -T2		Specimen -T3		Specimen -T4		Specimen -T5	
Weld Beads Tested	Heat Input, Kj/in(cm)	Weld Beads Tested	Heat Input, Kj/in(cm)	Weld Beads Tested	Heat Input, Kj/in(cm)	Weld Beads Tested	Heat Input, Kj/in(cm)	Weld Beads Tested	Heat Input, Kj/in(cm)
#195	44(17.3)	#72	58(22.8)	#20*	55(21.6)	#42*	48(18.9)	#130*	36(14.2)
196	39(15.4)	73	54(21.2)	21*	33(13.0)	43*	45(17.7)	131*	37(14.5)
197	38(14.9)	77	44(17.3)	22*	42(16.5)	46*	44(17.3)	138*	37(14.5)
204	42(16.5)	78	47(18.5)	23*	42(16.5)	47*	51(20.0)	139*	36(14.2)
205	40(15.7)	79	51(20.0)	24*	48(18.9)	50*	50(19.7)	140*	40(15.7)
206	42(16.5)	83	50(19.7)	25*	39(15.4)	51*	47(18.5)	146*	34(13.4)
207	40(15.7)	84	53(20.8)	26*	47(18.5)	52*	45(17.7)	147*	36(14.2)
215	36(14.2)	85	63(24.8)	27*	41(16.1)	96*	44(17.3)	148*	39(15.4)
216	36(14.2)	89	50(19.7)	29*	37(14.6)	97*	54(21.2)	154*	37(14.6)
		90	50(19.7)			101*	44(17.3)	155*	37(14.6)
		91	46(18.1)			102*	47(18.5)	163*	35(13.8)
	Avg. 39(15.3)		Avg. 51(20)		Avg. 43(16.9)		Avg. 47(18.5)		Avg. 37(14.5)

*Backside of weld joint

TABLE XXXII -- RESULTS OF R_C HARDNESS TRAVERSE, WELDMENT PD-4834 (See Figure 42)

Loc. No.	Rc No.	Zone	Loc. No.	Rc No.	Zone	Loc. No.	Rc No.	Zone	Loc. No.	Rc No.	Zone
1.	35		26.	35		51.	39	WELD	76.	41	
2.	35	BM	27.	36		52.	35		77.	40	
3.	34		28.	36		53.	37		78.	36	
4.	42	HAZ	29.	38		54.	37		79.	40	BM
5.	38		30.	39		55.	36		80.	38	
6.	37		31.	36		56.	39		81.	38	
7.	38		32.	41	WELD	57.	37		82.	43	
8.	39		33.	35		58.	38	BM	83.	42	
9.	31		34.	38		59.	34		84.	36	
10.	38		35.	35		60.	36		85.	42	
11.	38		36.	35		61.	35		86.	35	
12.	36		37.	41	HAZ	62.	35		87.	40	
13.	34	WELD	38.	36		63.	35		88.	37	WELD
14.	38		39.	34		64.	39		89.	37	
15.	35		40.	35		65.	40	HAZ	90.	36	
16.	34		41.	35		66.	39		91.	44	
17.	33		42.	36		67.	45		92.	45	
18.	38		43.	36	BM	68.	40		93.	48	
19.	39		44.	36		69.	42	WELD	94.	44	
20.	35		45.	37		70.	45		95.	39	
21.	36		46.	36		71.	36		96.	42	BM
22.	35		47.	37		72.	43	HAZ	97.	43	
23.	37	BM	48.	39	HAZ	73.	39		98.	41	
24.	37		49.	38	WELD	74.	36		99.	43	
25.	*NR		50.	38		75.	39		100.	40	WELD

*NR - Not Recorded

TABLE XXXII (Continued)

Loc. No.	Rc No.	Zone
101.	40	
102.	43	
103.	41	
104.	41	
105.	46	
106.	42	
107.	41	
108.	42	
109.	46	WELD
110.	41	
111.	40	
112.	45	
113.	38	
114.	45	
115.	38	
116.	45	
117.	39	
118.	44	

TABLE XXXIII -- OPTIMUM WELDING PROCEDURE FOR SPRAY ARC GMA WELDING 6" (15.24cm) HY-150 STEEL IN FLAT POSITION

General Requirements

Base Material:	HY-150 Quenched and Tempered per MIL-S-24371 (SHIPS)[1]		
Welding Electrodes:	SMA Process, Type 14018AW per MI-30-CE/1 GMA Process, Type 140S per MI-30 BE/1		
Joint Design:	Type B2V3 per MIL-STD-0022B (SHIPS) Double Vee Butt Joint 45°[2]		
Type Restraint:	None	Pre-Weld Cleaning: Interpass Cleaning:	Grinding and Wire Brush Slag Pick and Wire Brush
Inspection:			
Fit-Up:	Visual	Root and Backside:	Magnetic Particle (MT)
Final:	Magnetic Particle (MT), Radiography (R.T.) and Ultrasonic (U.T.)		
Applicable Inspection Standards:	MT: MIL-STD-271D		
RT:	MIL-STD-271D and NavShips 0900-003-9000, Gr. I		
U.T.:	NavShips 0900-006-3010, CLI		

Notes:

1. Modified to allow maximum carbon content of 0.13%.
2. Double bevel joint preparations are flame cut.

TABLE XXXIII -- OPTIMUM WELDING PROCEDURE FOR SPRAY ARC GMA WELDING 6" (15.24cm) HY-150 STEEL IN FLAT POSITION (Continued)

Welding Parameters	Root Passes	Fill Passes
Pass Numbers	1 & 2	Remainder
Process	SMA	GMA
Manual, Semi-Automatic	Manual	Semi-Automatic
Position	Flat	Flat
Electrode Type	E-14018AW	140-S
Electrode Size	1/8" (0.32cm)	1/16" (0.16cm)
Arc Voltage	21-23	25-26
Wire Feed Speed	----	180-200 ipm (458-507cm/min)
Welding Current	120-130 Amps.	280-310 Amps.
Type Current & Polarity	DCRP	DCRP
Shielding Gas	----	Argon/2% O_2
Shielding Gas Flow Rate	----	45-55 CFH
Preheat Temperature	200°F (93°C) Min.	200°F (93°C) Min.
Interpass Temperature	300°F (149°C) Max.	275°F (135°C) Max.
Gas Cup Size	----	#8 & 10
Contact Tip to Work Dist.	----	5/8" (1.5cm) (Approximately)
Gas Cup to Work Distance	----	1/2" (1.2cm) (Approximately)
Travel Speed	4.5 ipm (10-12cm/min)	12-16 ipm (30-40 cm/min)
Heat Input (Max.)	40KJ/in(15.7KJ/cm)	45KJ/in (17.7KJ/cm)

Notes:
1. The welding voltage to be measured at the wire drive unit.
2. A prepurge and postpurge capability shall be provided.
3. Weldment temperature shall be maintained @200°F (93°C) minimum at all times during welding and @250-300°F(121-149°C) between shifts and overnight until the completion of welding.
4. Weldment temperature measured at point of weld start.

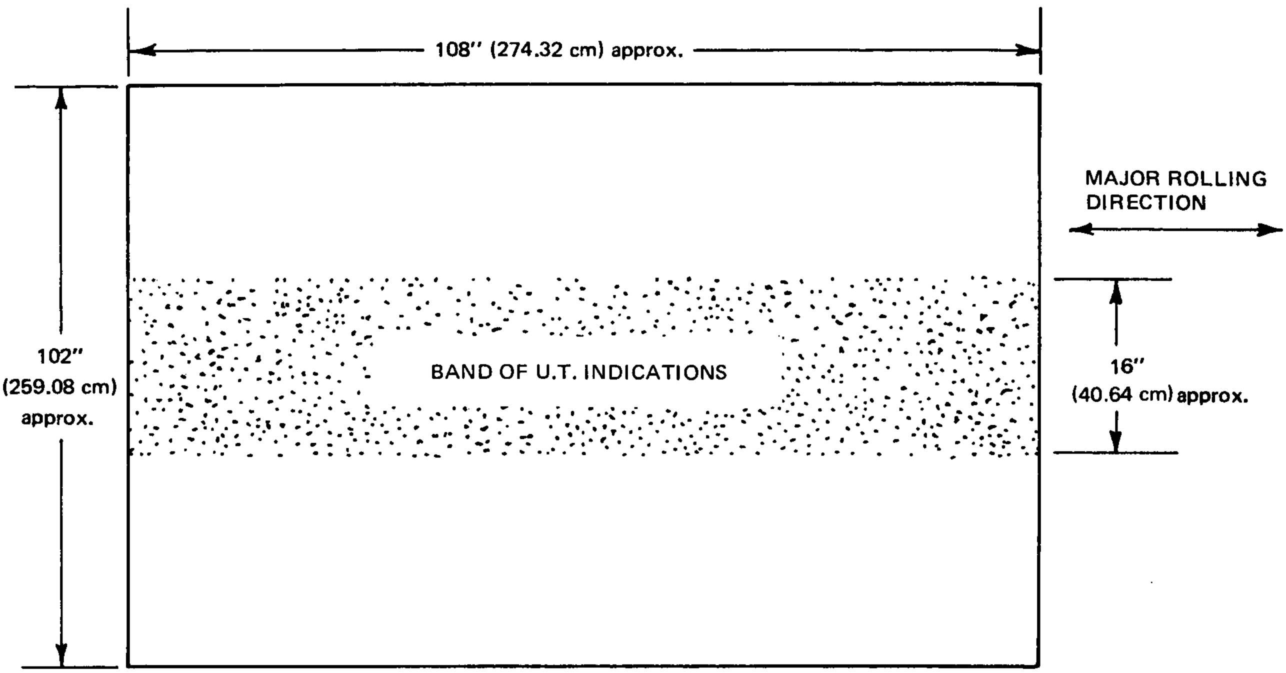


PLATE F4602

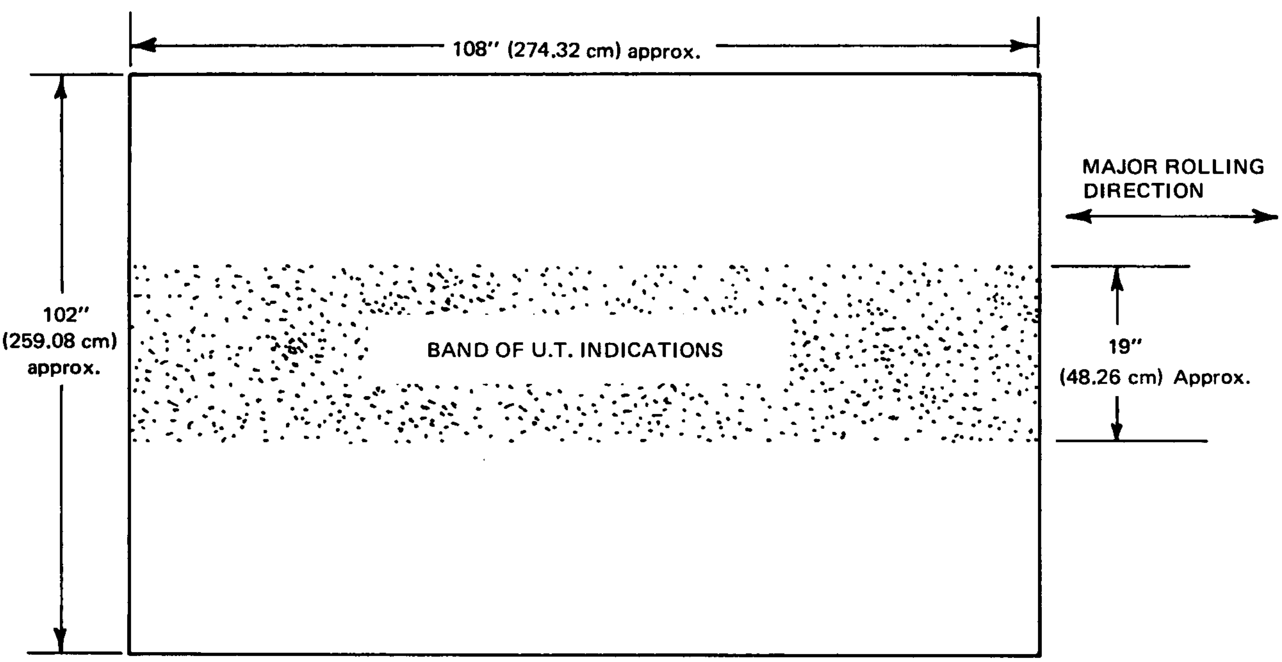


PLATE F4603

FIGURE 1 – DEFECT PATTERNS IN BASE PLATES

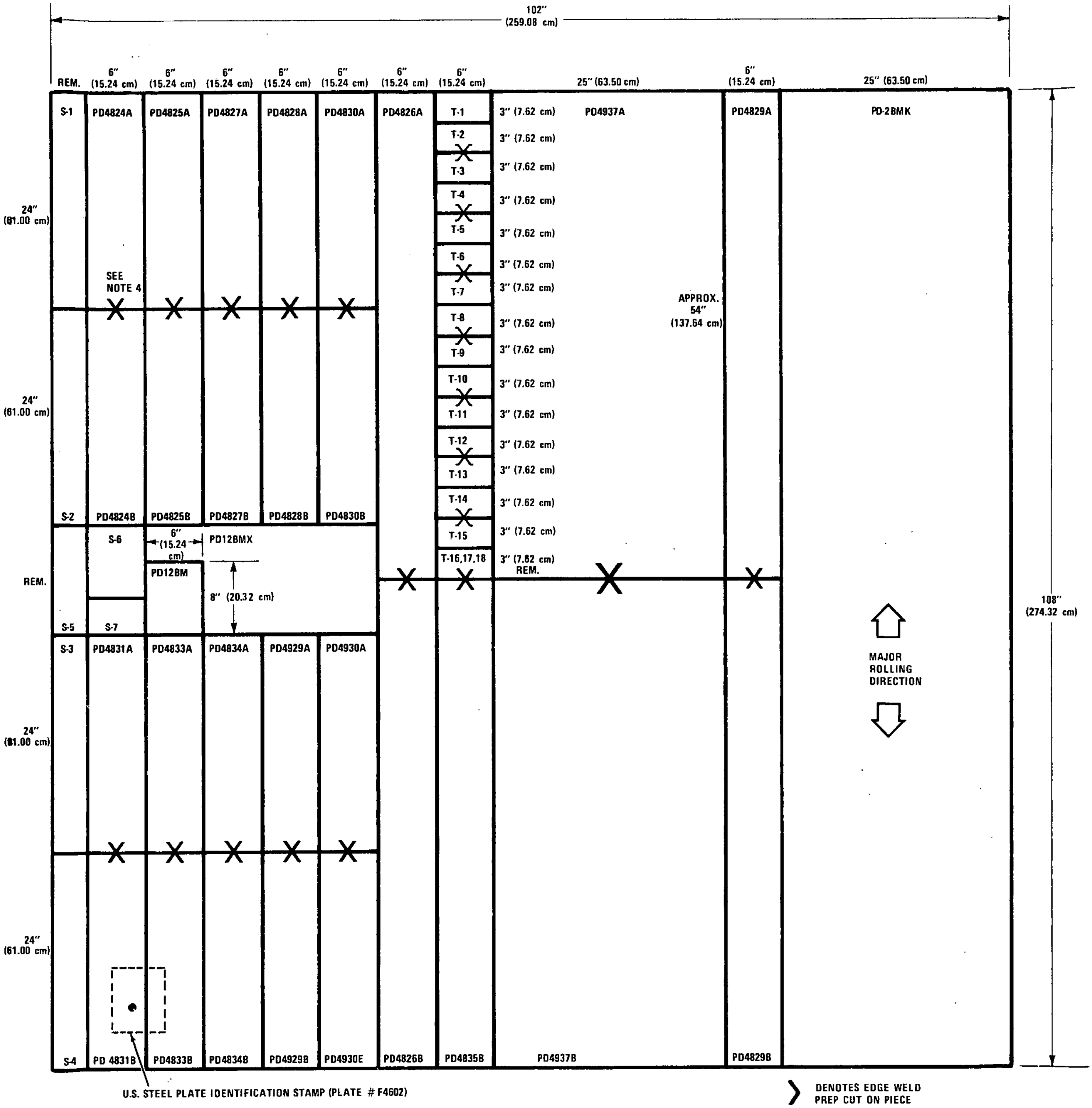


FIGURE 2 MATERIAL LAYOUT OF MASTER PLATE F-4602

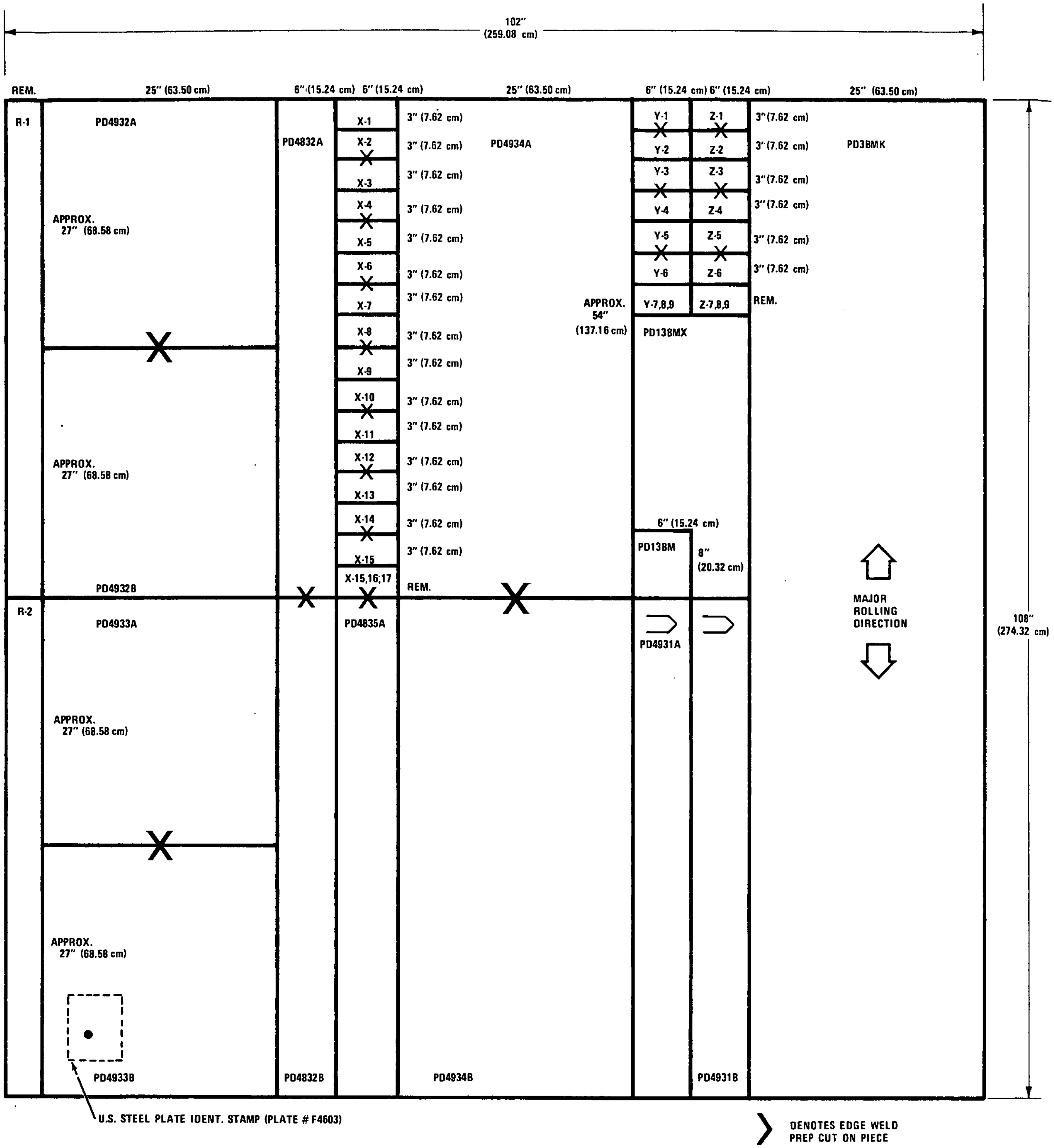


FIGURE 3 MATERIAL LAYOUT OF MASTER PLATE F-4603

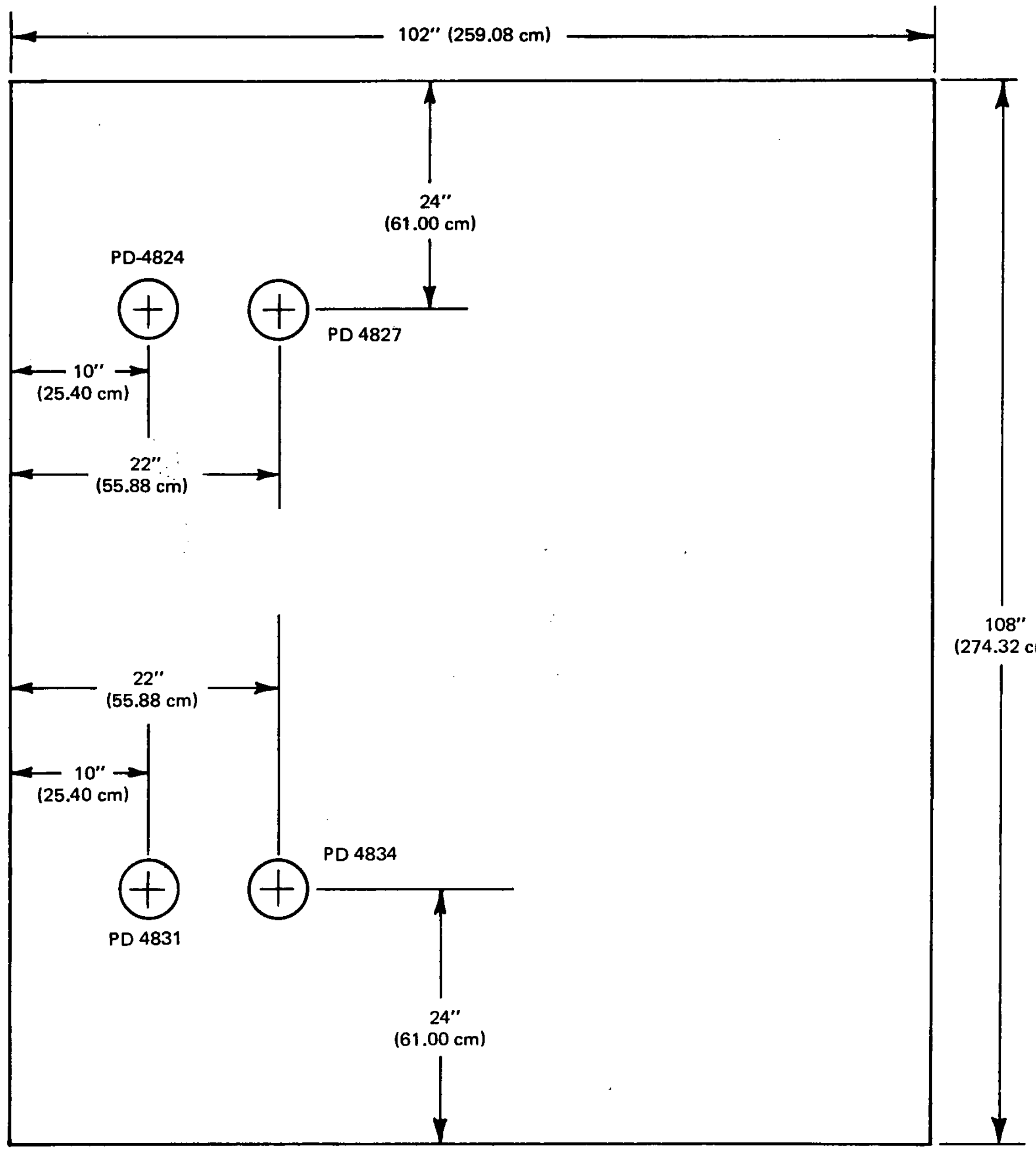
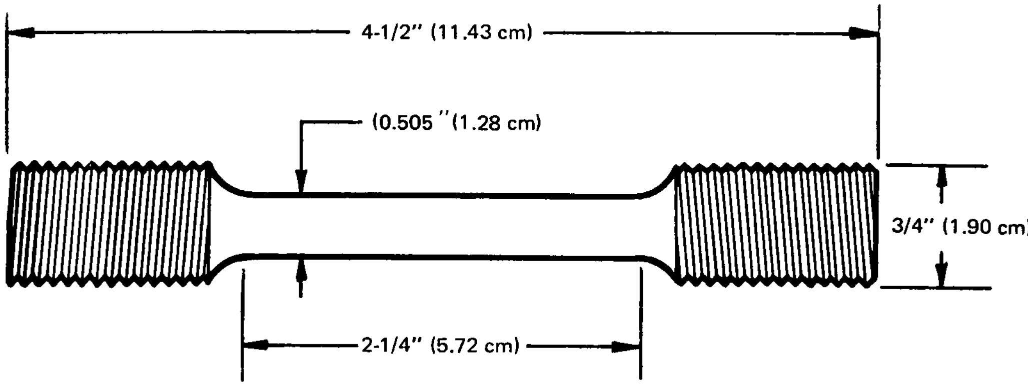
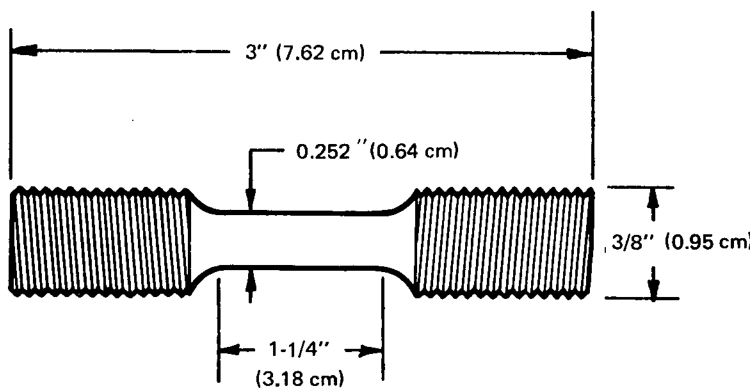


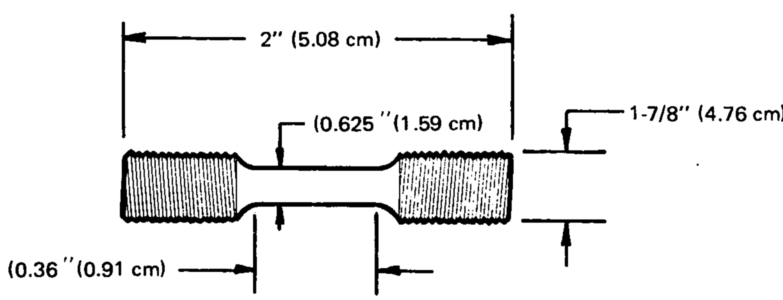
FIGURE 4 – LOCATIONS OF HARDNESS TEST BLOCKS, PLATE F 4602



0.505" (1.28 cm)



(0.252 "(0.64 cm)



SHORT–TRANSVERSE

FIGURE 5 – TENSILE SPECIMEN DIMENSIONS AND DETAILS

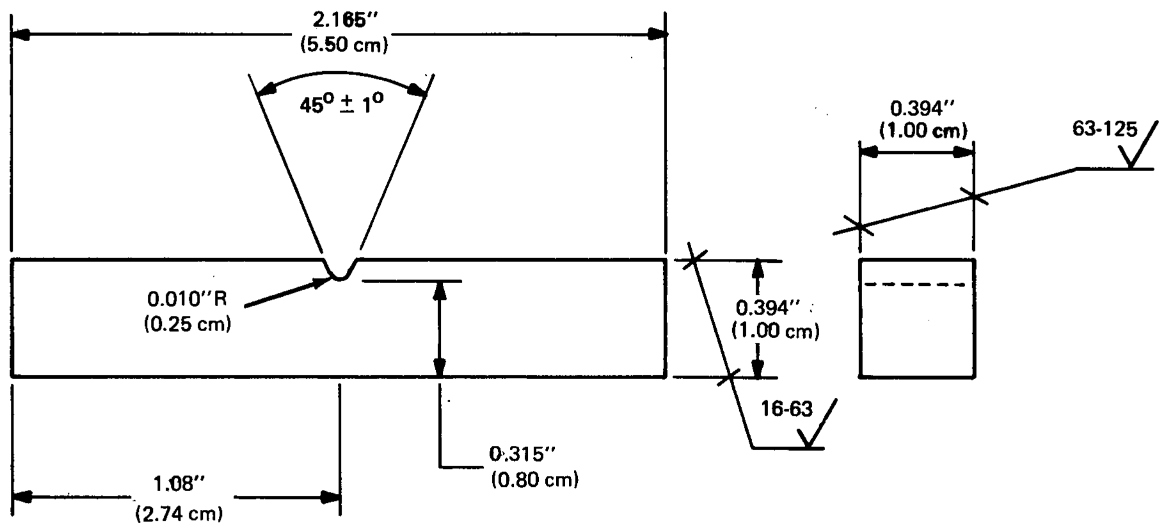
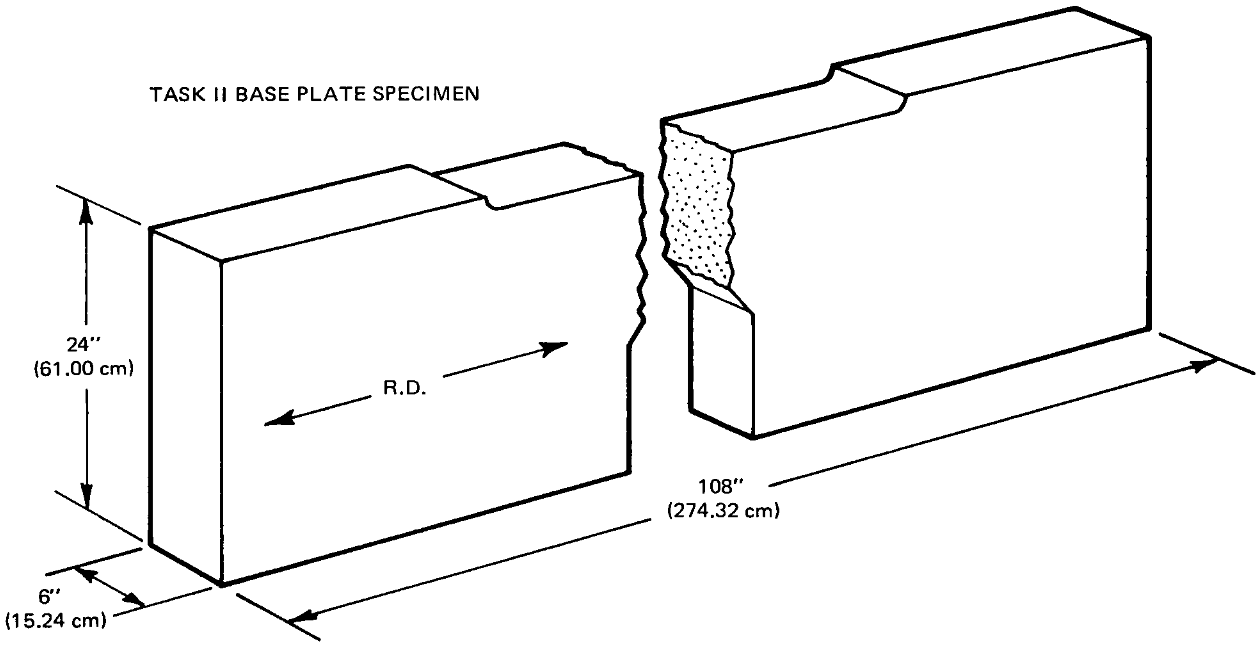


FIG. 6

CHARPY V-NOTCH IMPACT SPECIMEN

TASK II BASE PLATE SPECIMEN



NOTCH DETAILS:

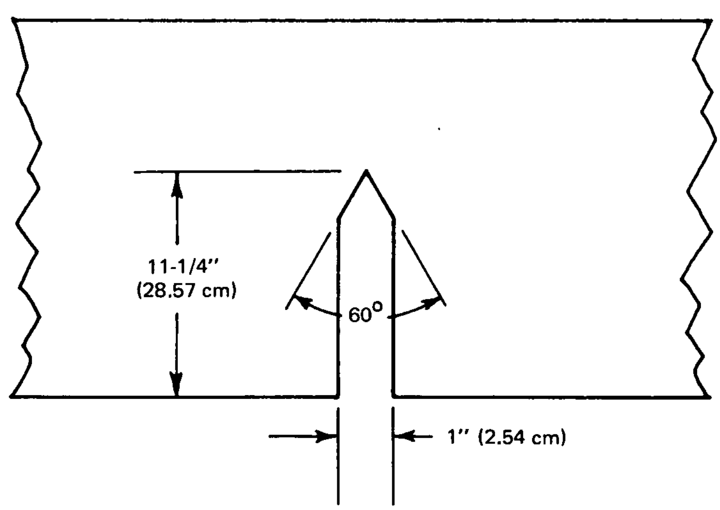


FIGURE 7 – BASE METAL EDGE-NOTCHED FRACTURE TOUGHNESS BEND SPECIMEN DIMENSIONS AND DETAILS

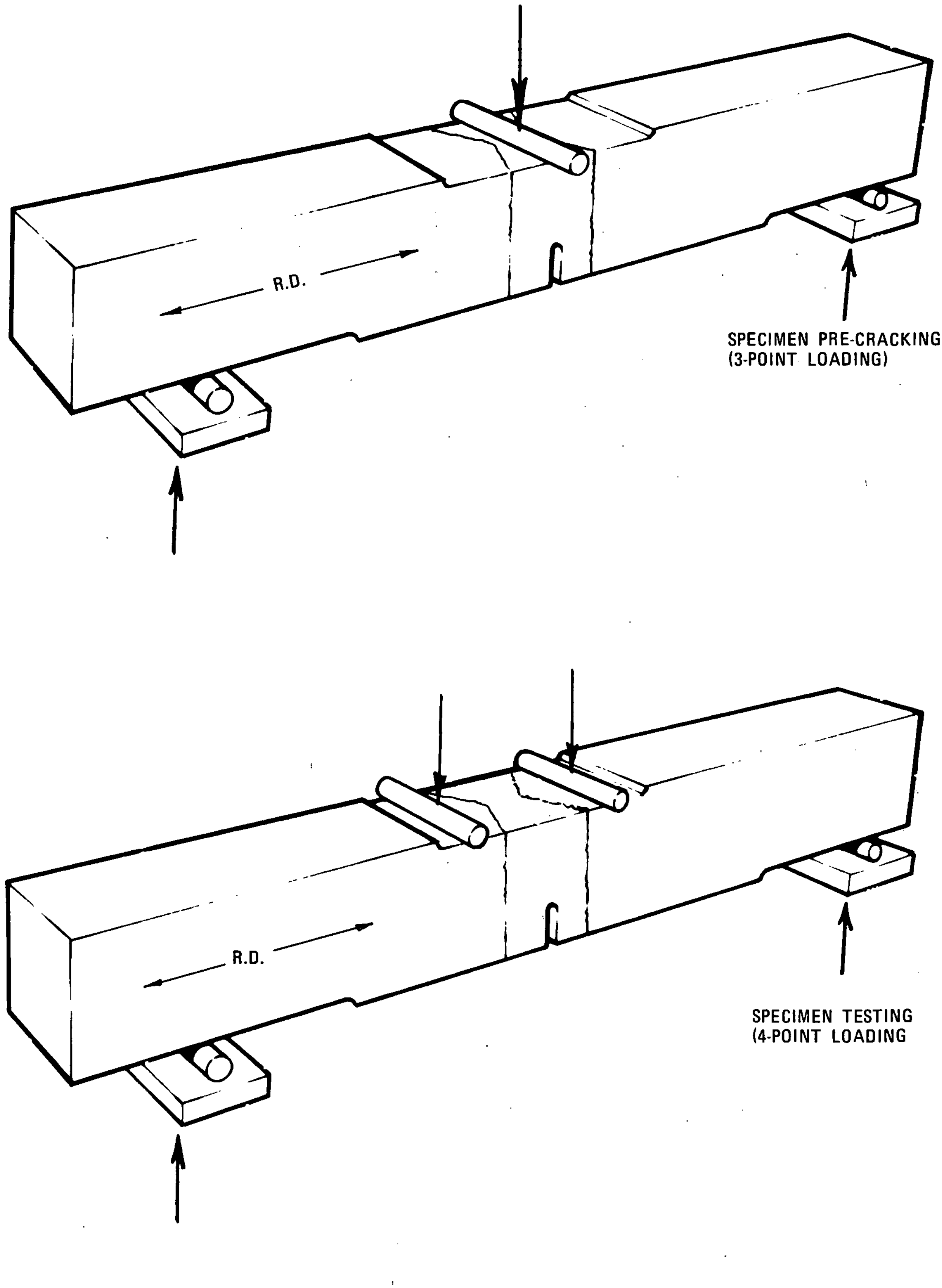


FIGURE 8 – METHODS OF LOADING USED IN PRE-CRACKING AND TESTING ALL K_{IC} SPECIMENS OF THIS PROGRAM (WELD SPECIMEN SHOWN)

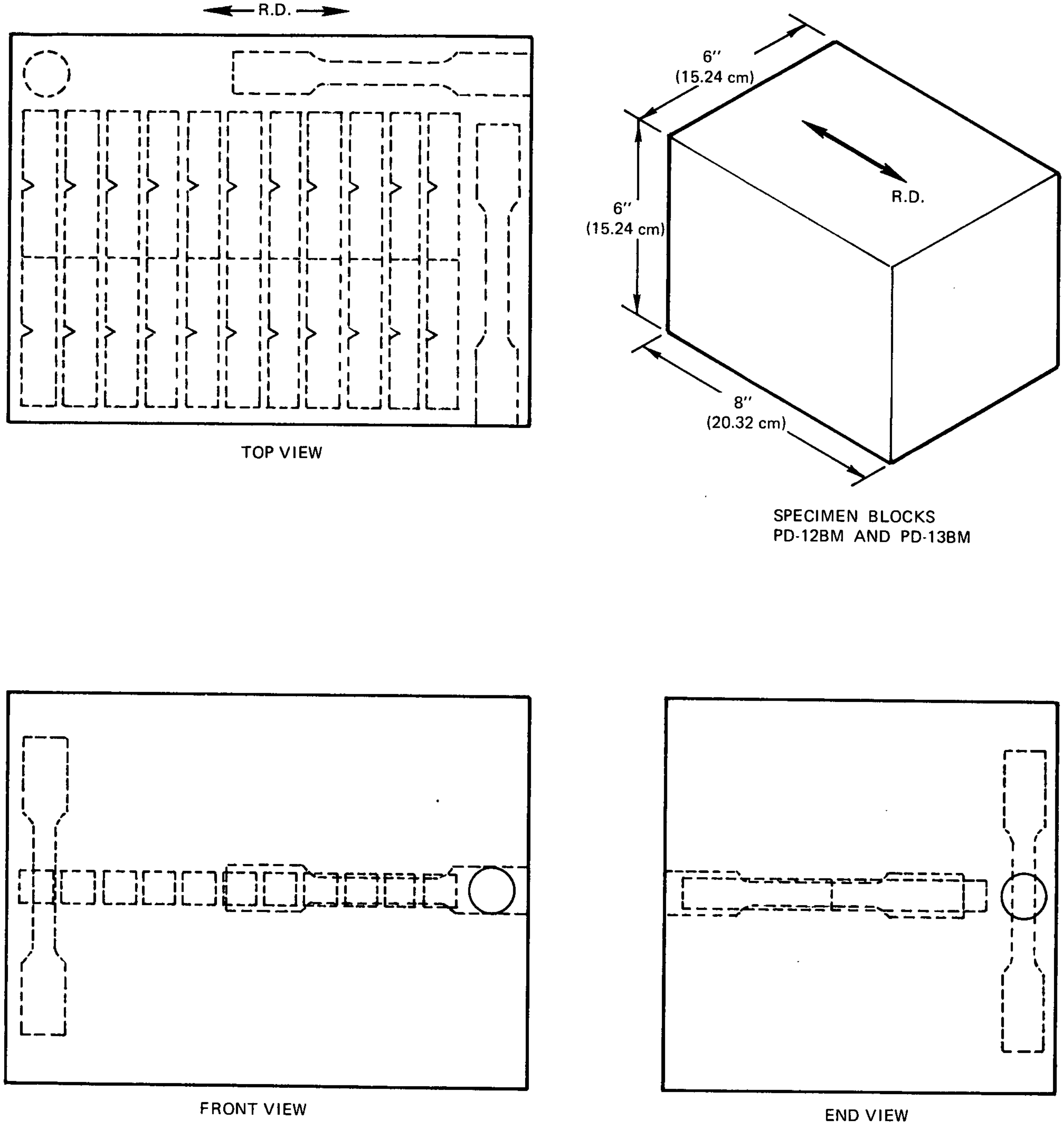
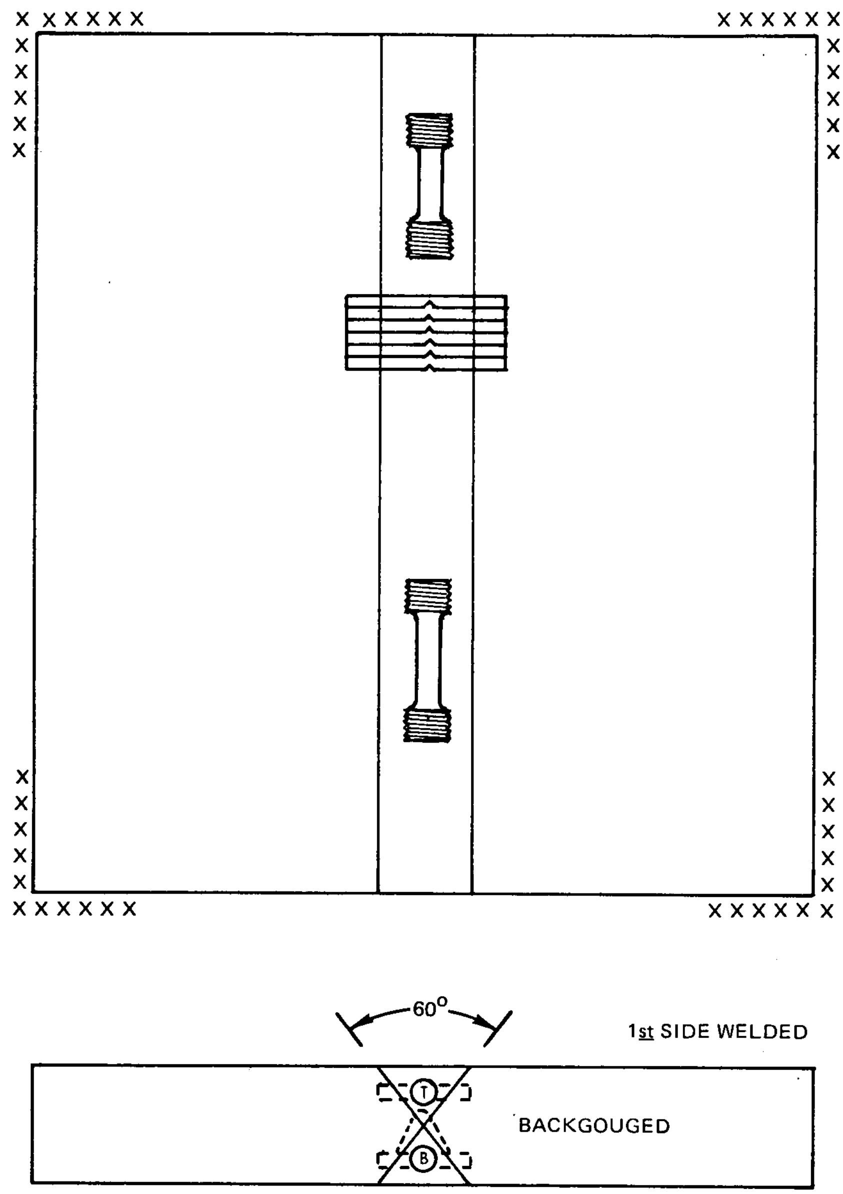


FIG. 9 – LOCATION AND ORIENTATION OF TENSILE AND CHARPY SPECIMENS WITHIN SPECIMEN BLOCKS TAKEN FROM MASTER PLATES F4602 AND F4603.



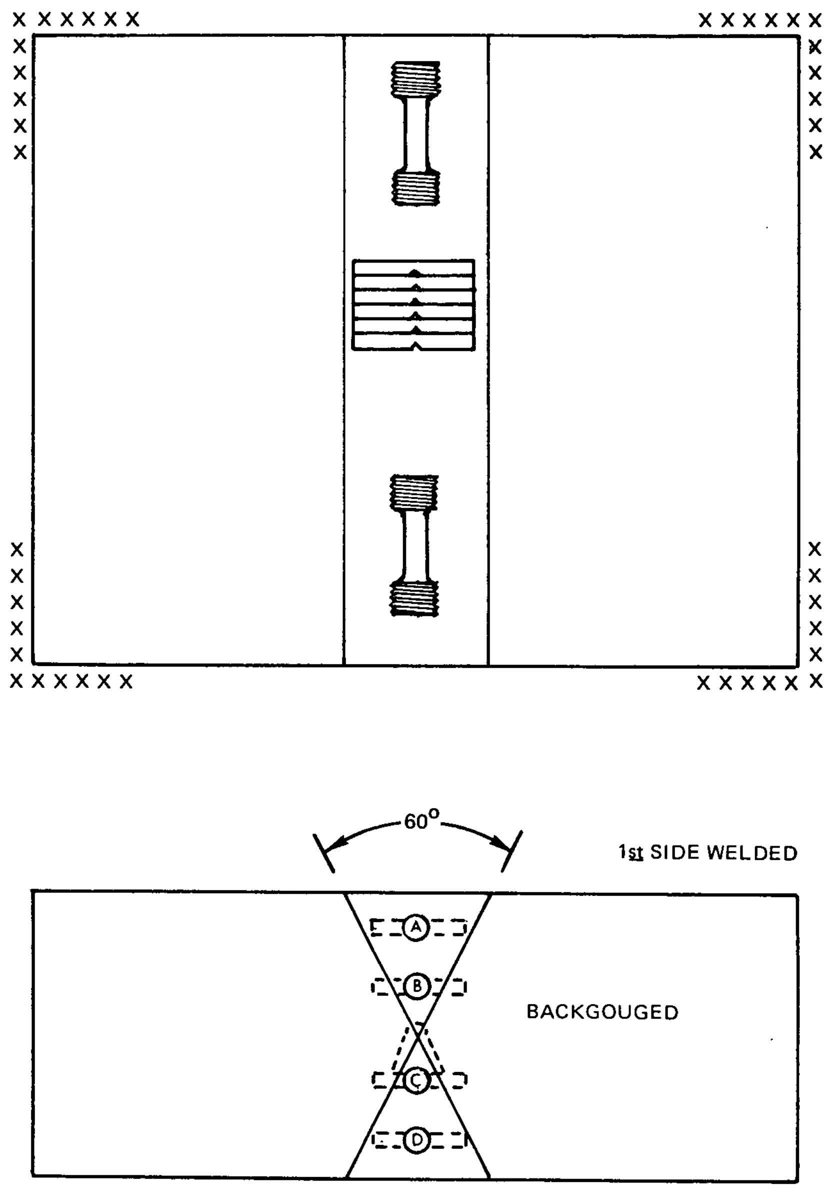
2" (5.08 cm) HY-80 BASE PLATE

RESTRAINT CONDITIONS:

FOR 1st SIDE WELDED - - WELDED WITH 1/2" (1.27 cm) FILLET WELDS TO 2" (5.08 cm) -THICK STEEL TABLE TOP.

FOR 2nd SIDE WELDED - - FOUR LARGE "C" CLAMPS, ONE AT EACH CORNER OF WELDMENT.

FIGURE 10 – WELD JOINT DESIGN AND SPECIMEN LOCATIONS, TEST PLATE PD-4836 (SMA)



4" (10.16 cm) HY-80 BASE PLATE

RESTRAINT CONDITIONS:

FOR 1st SIDE WELDED - - WELDED WITH 1/2" (1.27 cm) FILLET WELDS TO 2" (5.08 cm) -THICK STEEL TABLE TOP.

FOR 2nd SIDE WELDED - - FOUR LARGE "C " CLAMPS, ONE AT EACH CORNER OF WELDMENT.

FIGURE 11 – WELD JOINT DESIGN AND SPECIMEN LOCATIONS, TEST PLATE NO. PD-4837 (GMA)

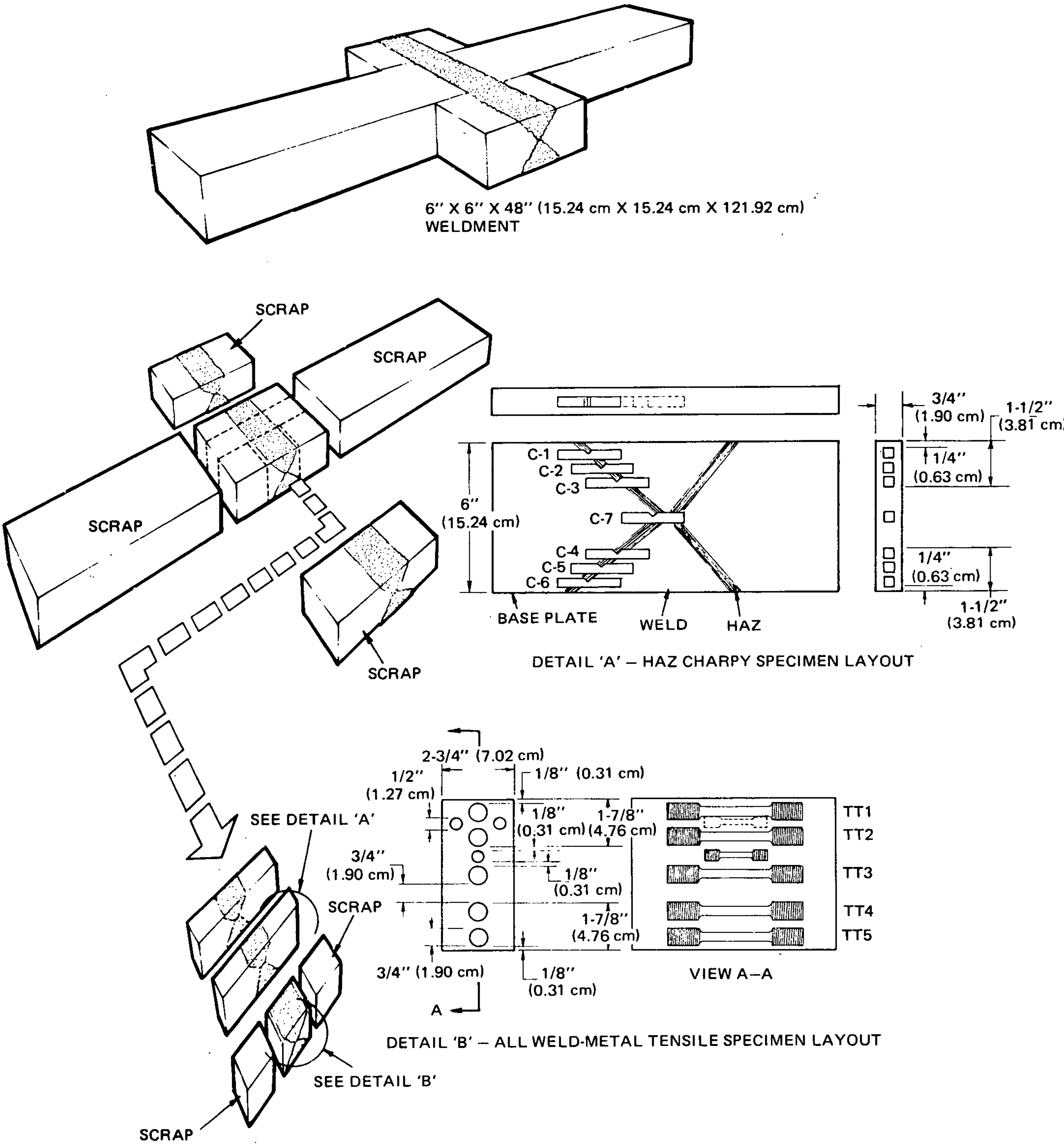


FIGURE 12 – TEST SPECIMEN LAY-OUT FOR TASK III WELDMENTS PD-4825, PD-4830, PD-4828 AND PD-4833

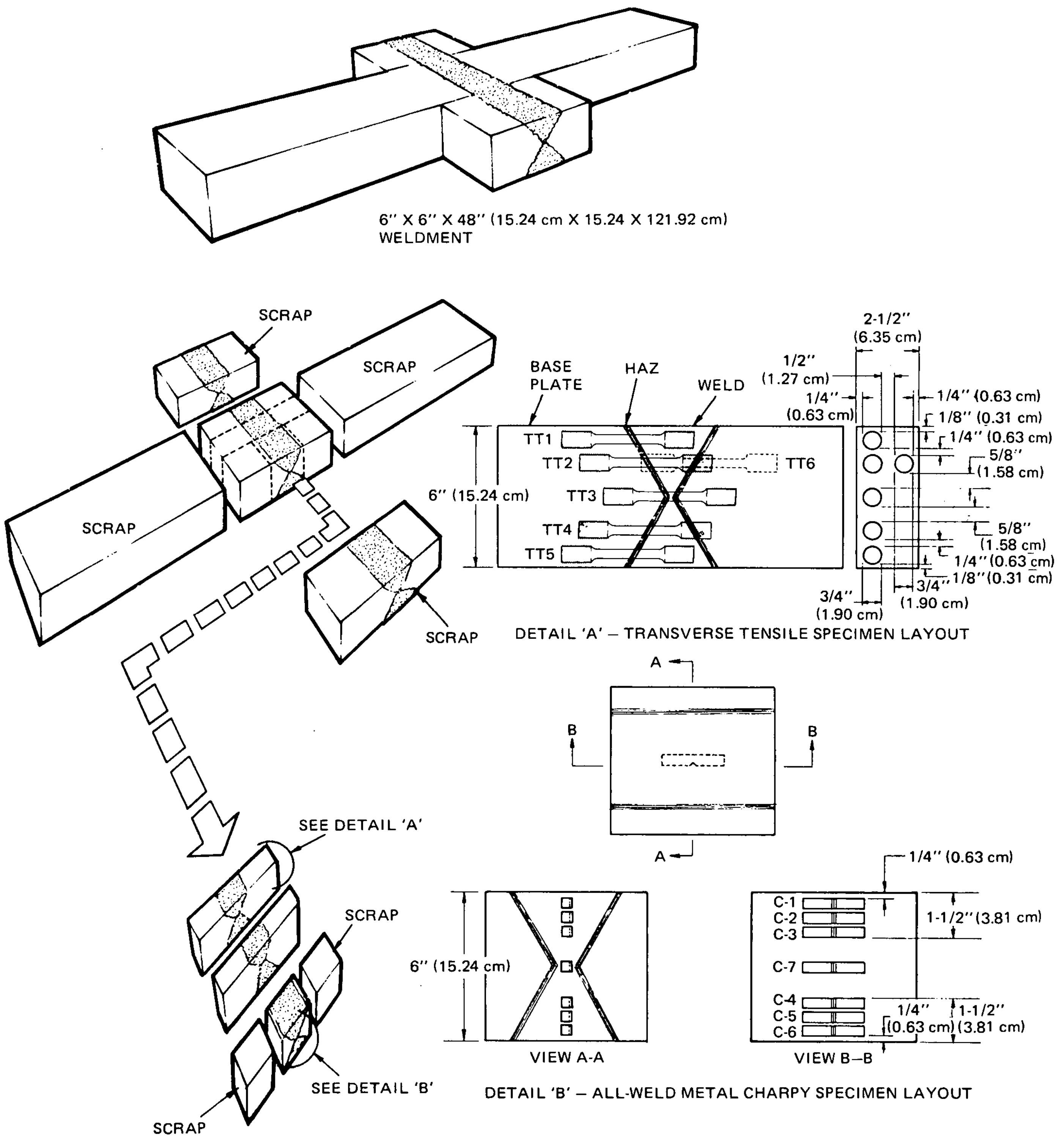


FIGURE 13 – TEST SPECIMEN LAY-OUT FOR TASK III WELDMENTS PD-4827, PD-4831, PD-4824 AND PD-4834

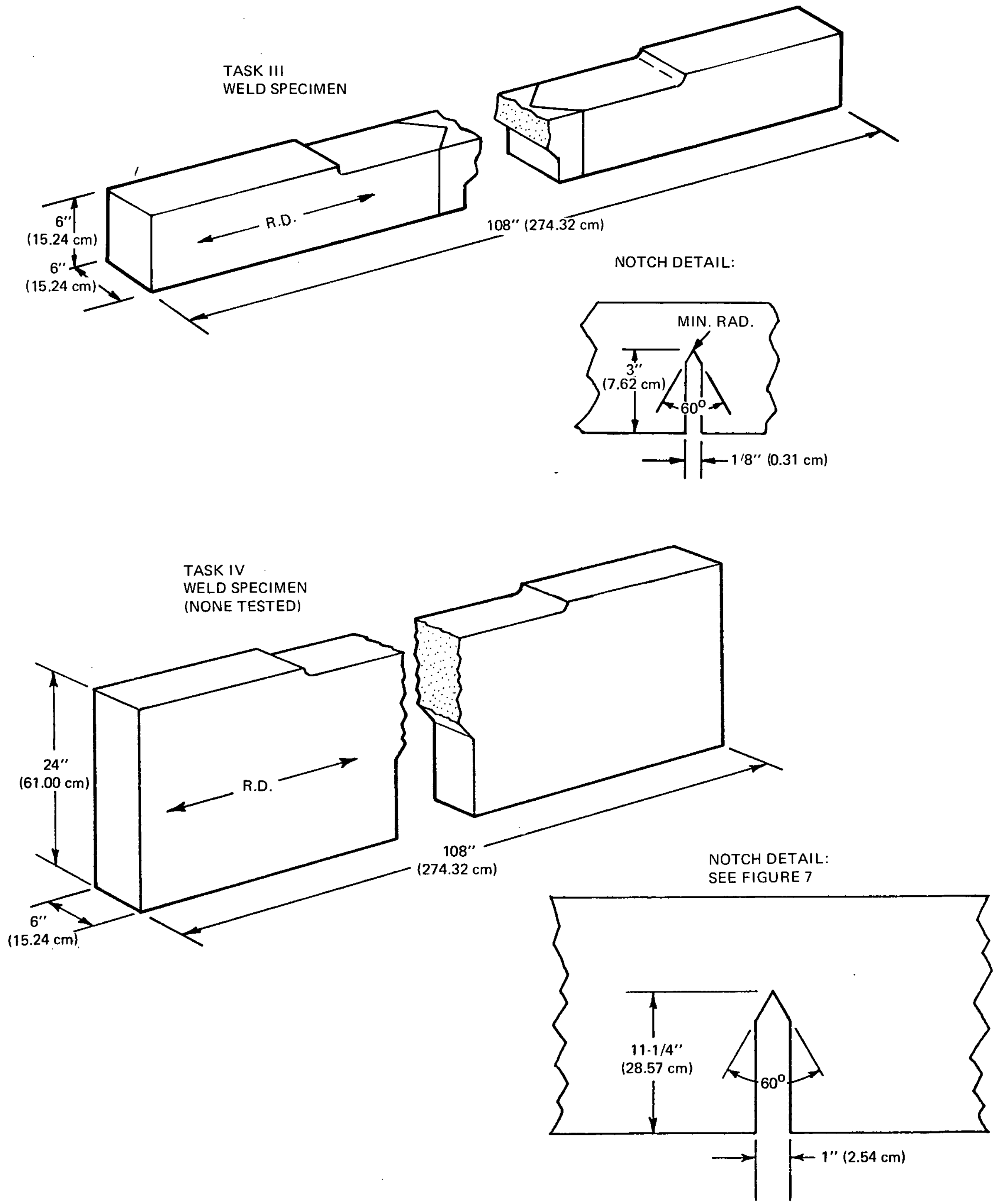


FIGURE 14 – WELD LOCATION AND ROLLING DIRECTION DETAILS FOR TASK III AND IV K_{IC} SPECIMENS, INCLUDING PD-4826, PD-4931, PD-4829 AND PD-4835

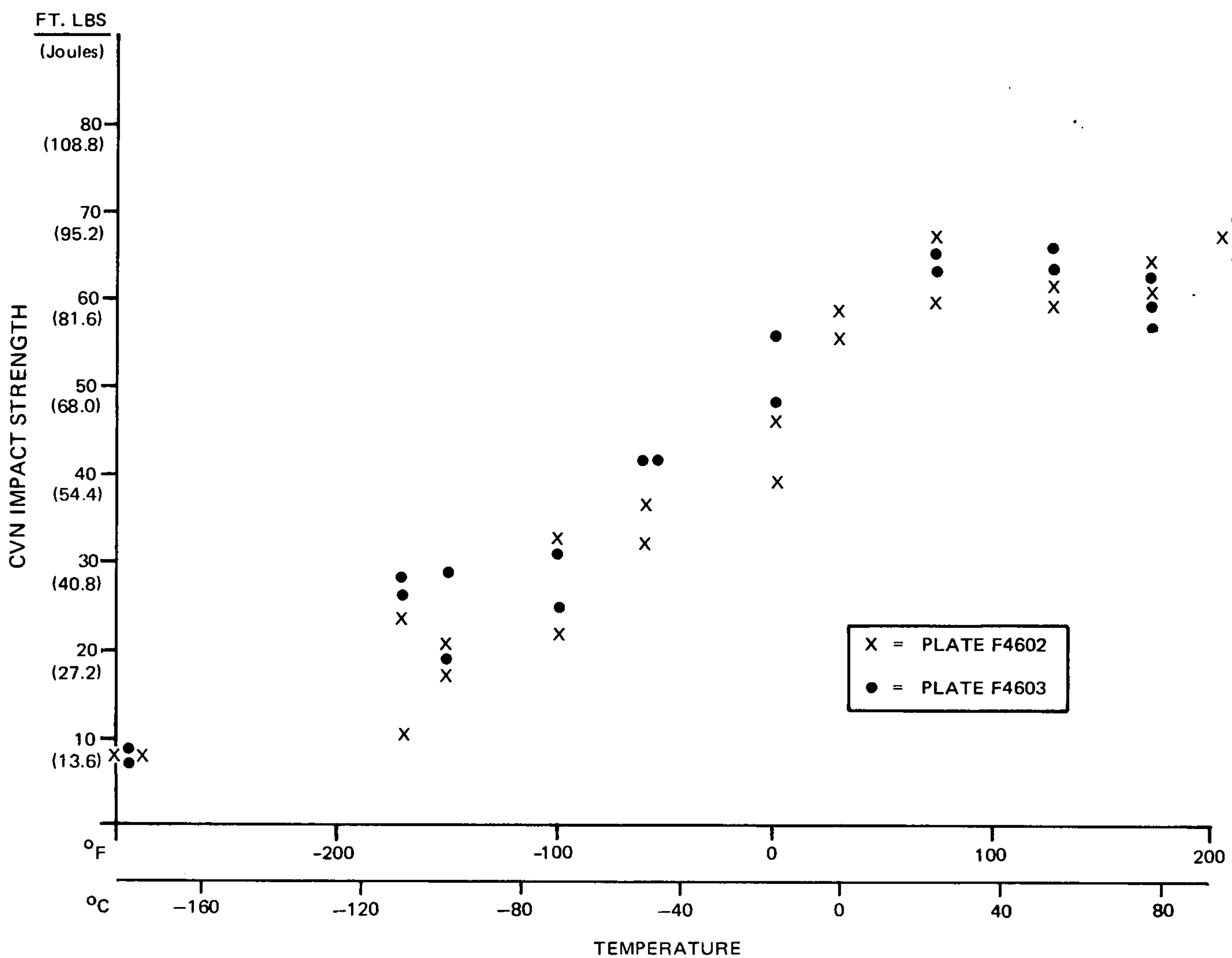


FIGURE 15 TRANSVERSE CVN IMPACT TEMPERATURE TRANSITION CURVE – PLATES F4602 and F4603

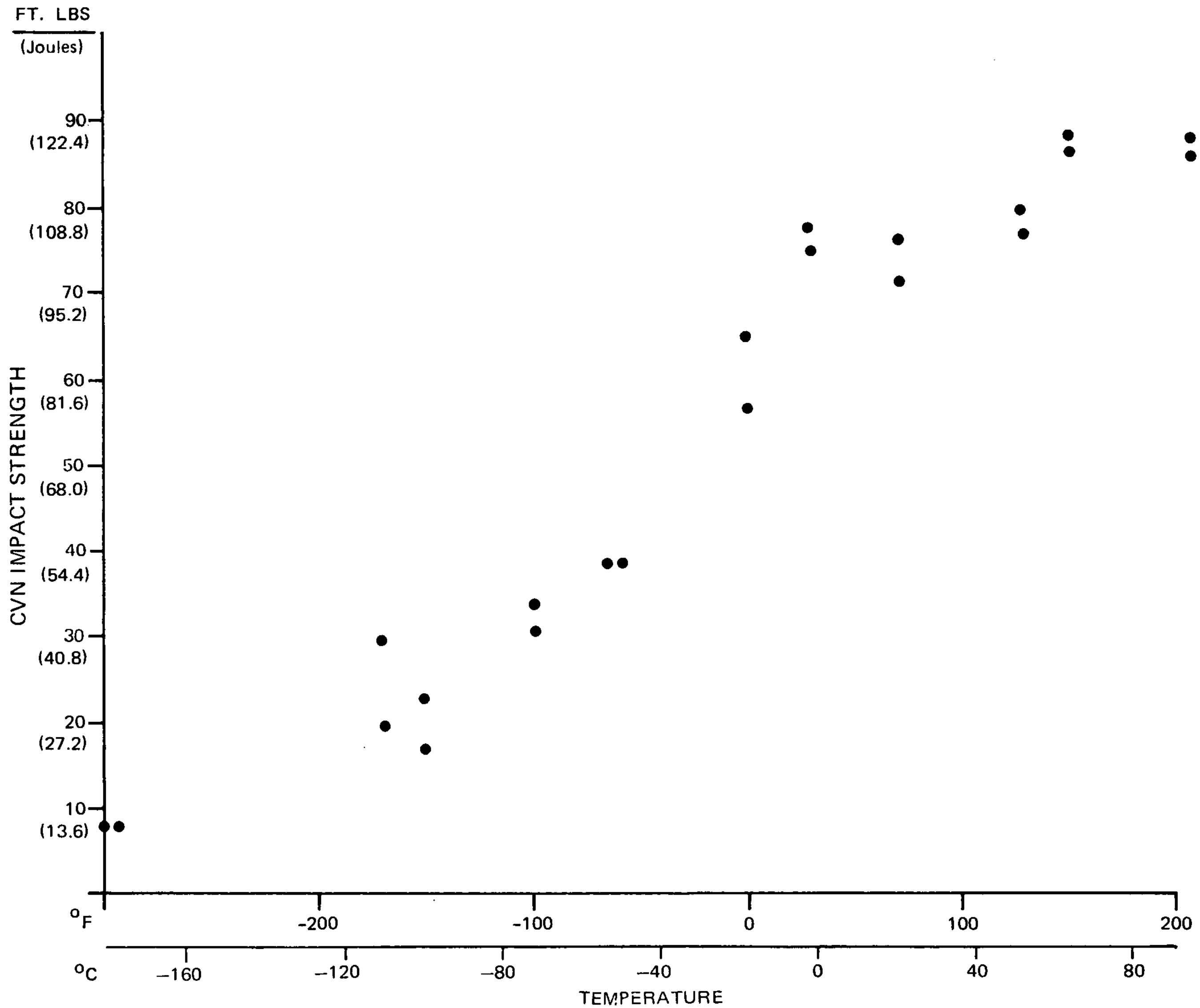
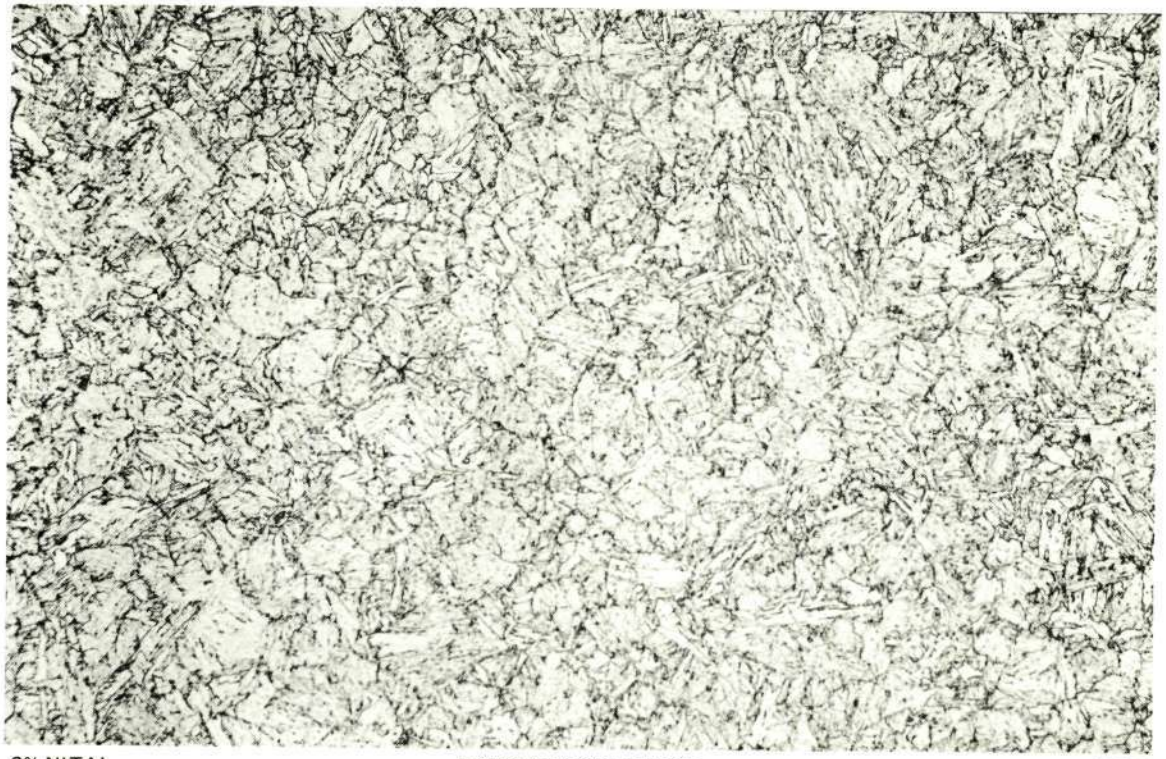
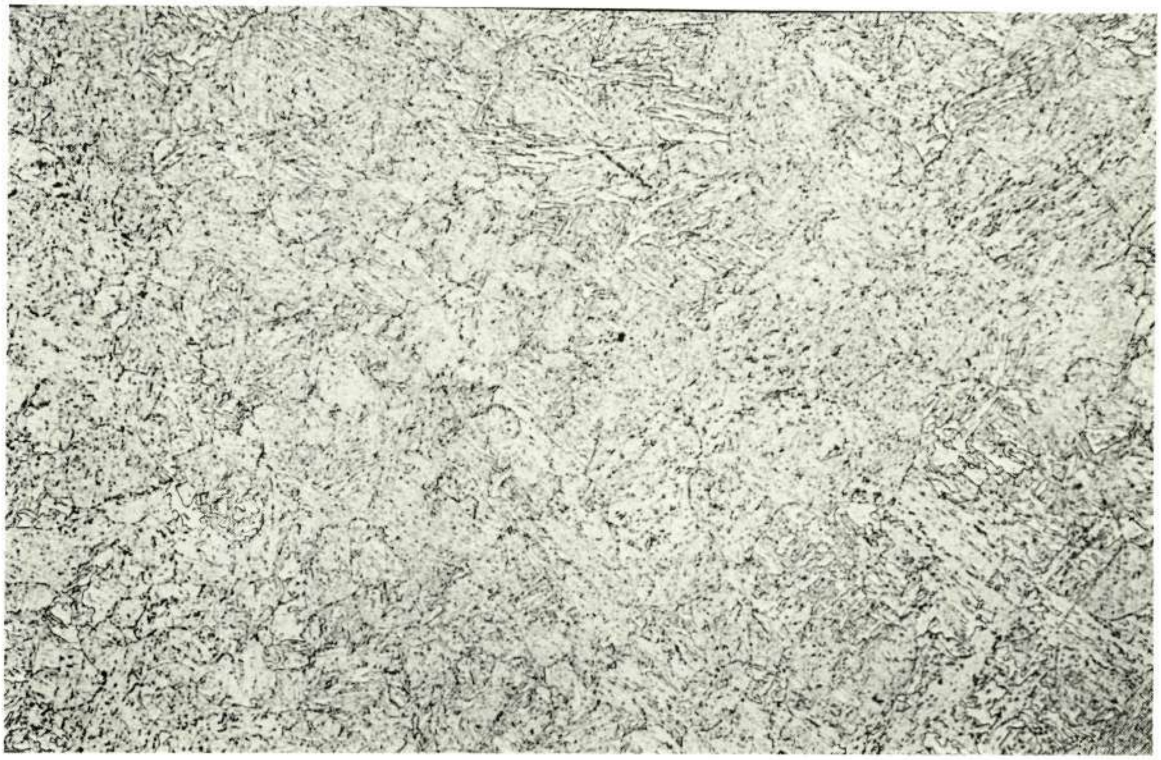


FIGURE 16 LONGITUDINAL CVN IMPACT TEMPERATURE TRANSITION CURVE – PLATE F4602



2% NITAL F4602 NEAR-SURFACE 400 X



2% NITAL F4602 MID-THICKNESS 400 X

FIGURE 17 – PHOTO MICROGRAPHS OF NEAR-SURFACE AND MID-THICKNESS AREAS OF PLATE F-4602

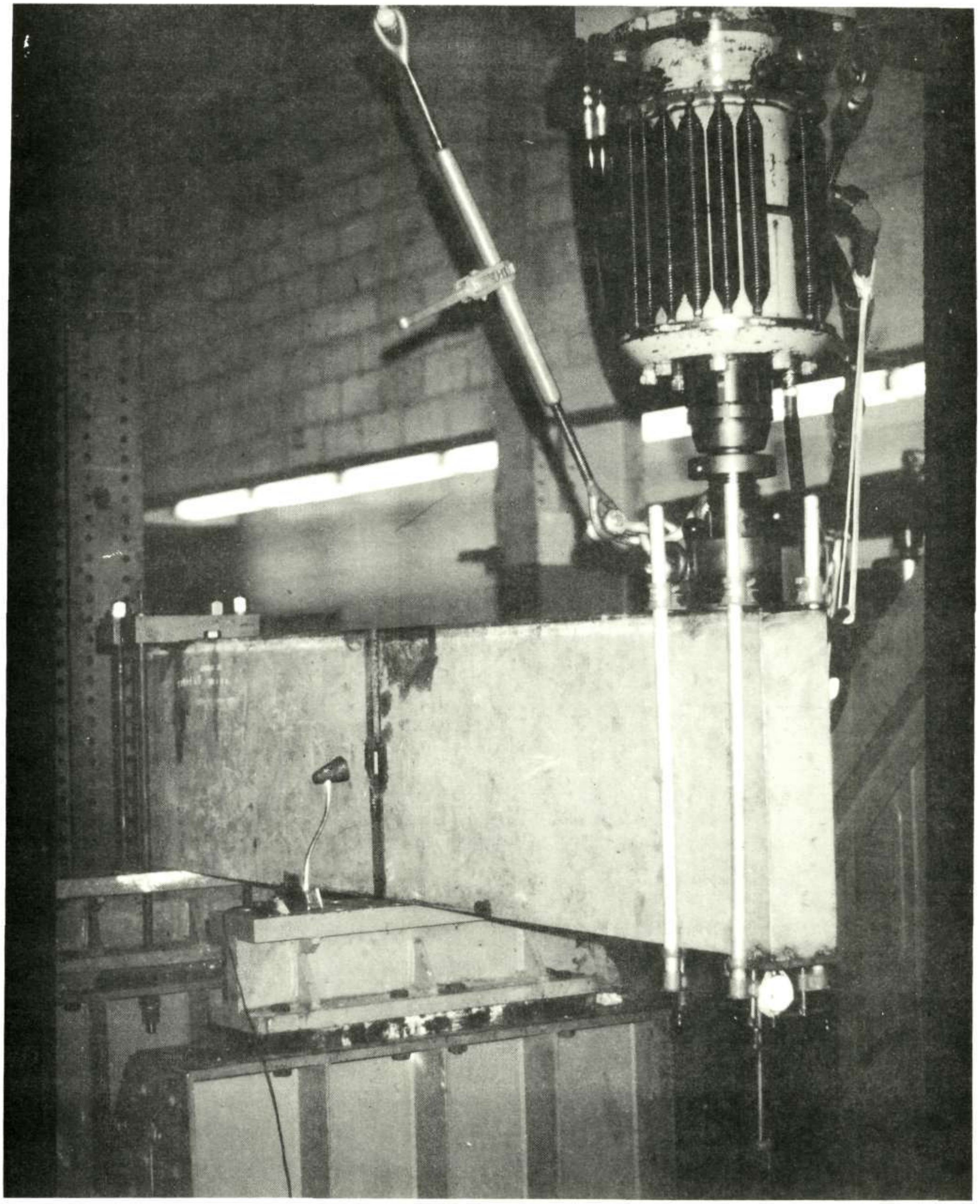


FIGURE 18 – BASE METAL K_{IC} SPECIMEN MOUNTED IN TEST FRAME FOR PRECRACKING

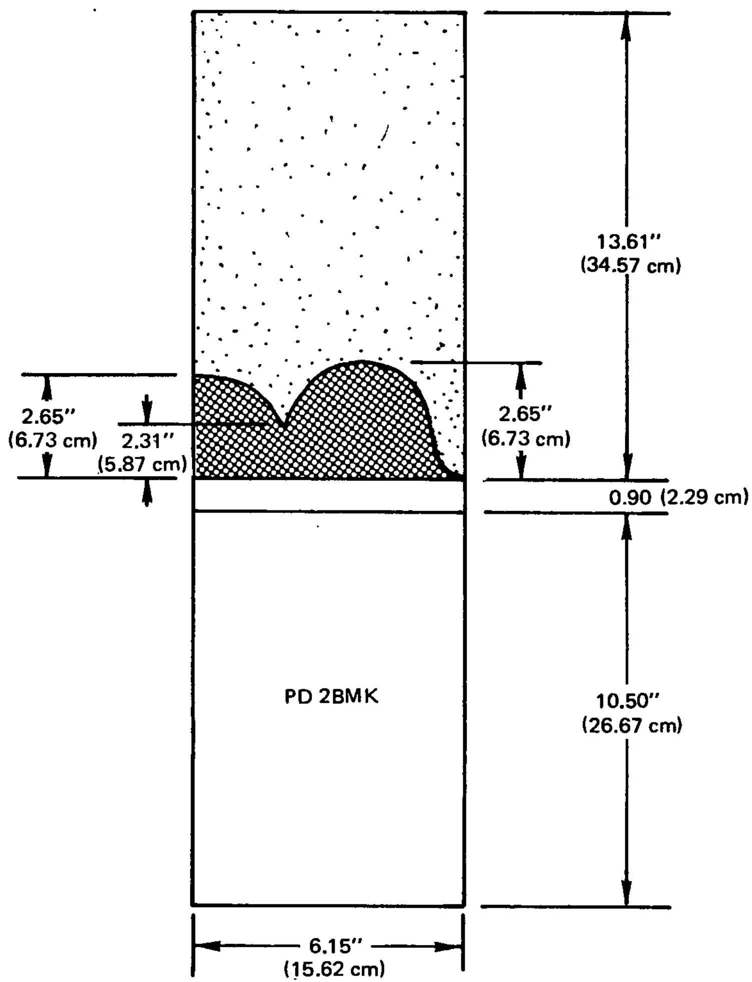


FIGURE 19 – PRECRACK DIMENSIONS AND DETAILS, BASE METAL FRACTURE TOUGHNESS TEST SPECIMEN PD-2BMK

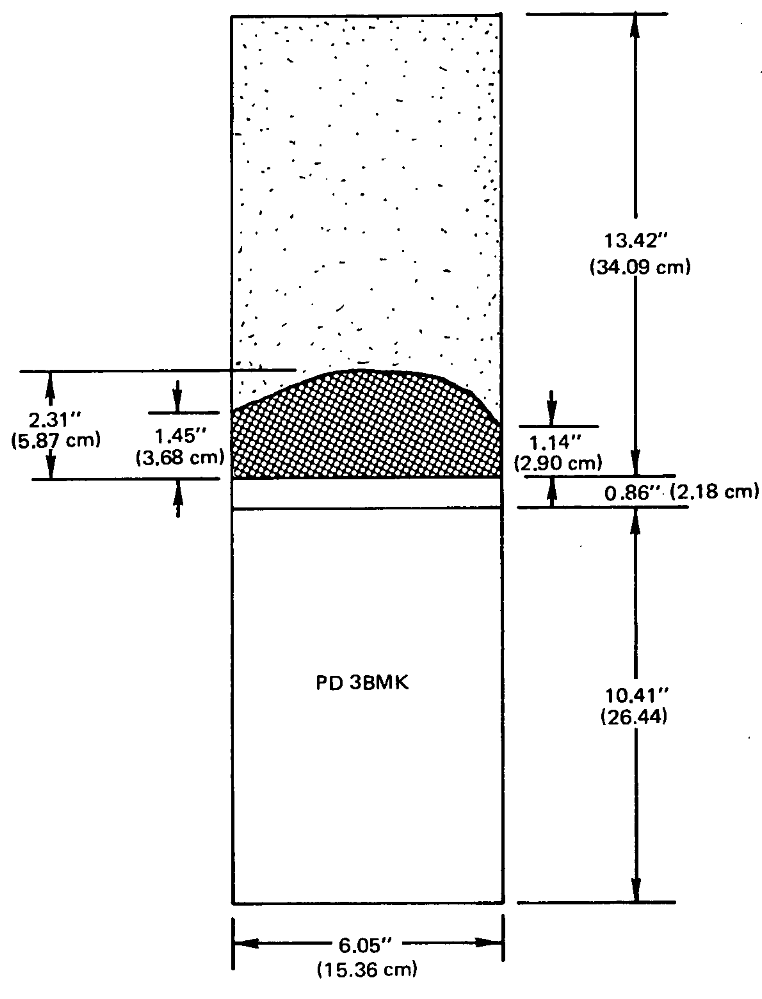
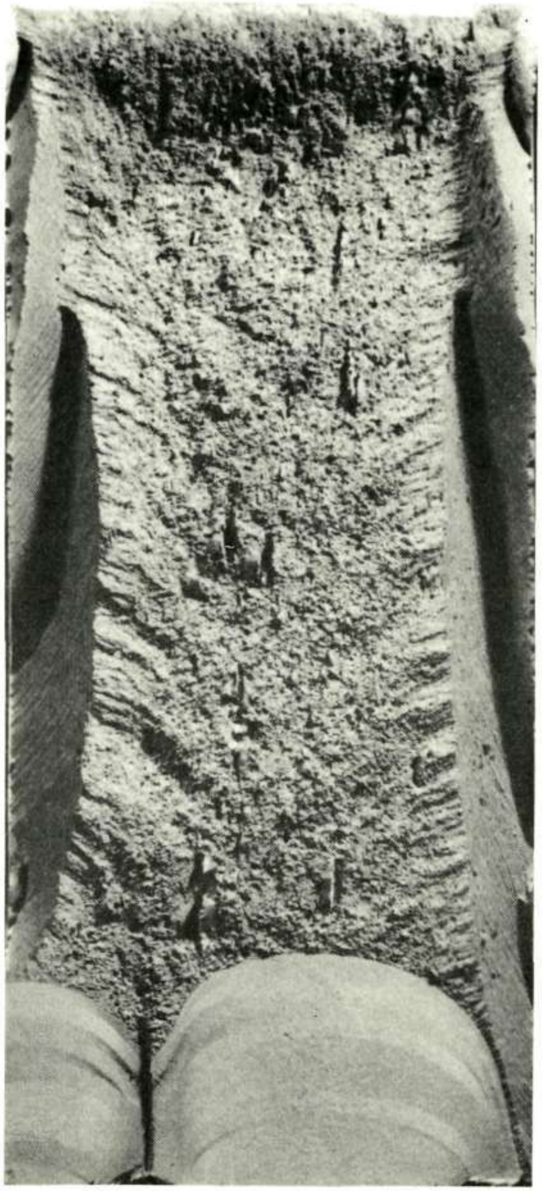


FIGURE 20 – PRECRACK DIMENSIONS AND DETAILS, BASE METAL FRACTURE TOUGHNESS TEST SPECIMEN PD-3BMK



PD-2BMK
PLATE F4602

PD-3BMK
PLATE F4603

FIGURE 21 – FRACTURE SURFACES, BASE METAL FRACTURE TOUGHNESS TEST SPECIMENS AFTER TESTING

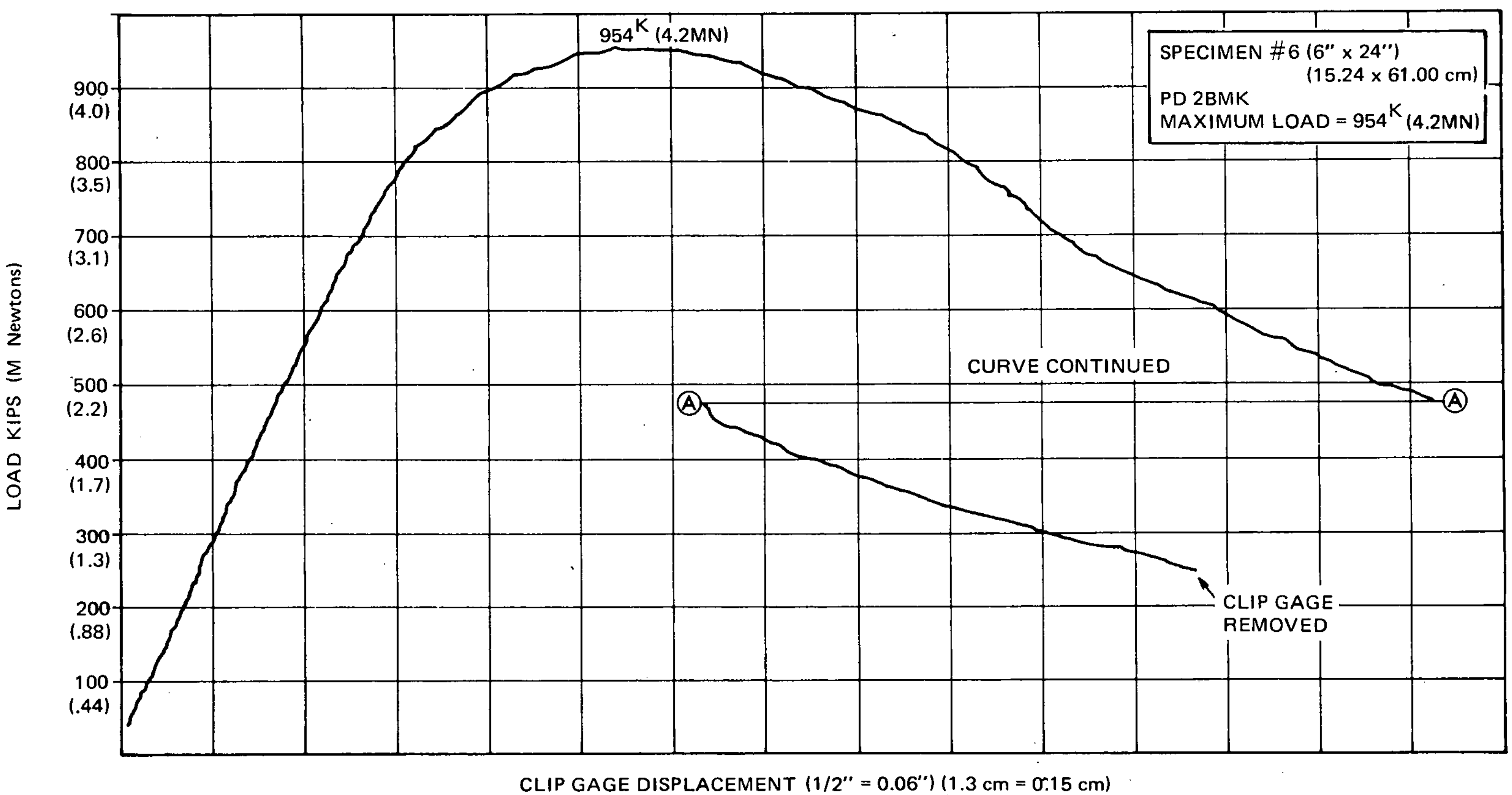


FIGURE 22 – LOAD-DISPLACEMENT CURVE FOR FRACTURE TOUGHNESS TEST OF SPECIMEN PD-2BMK

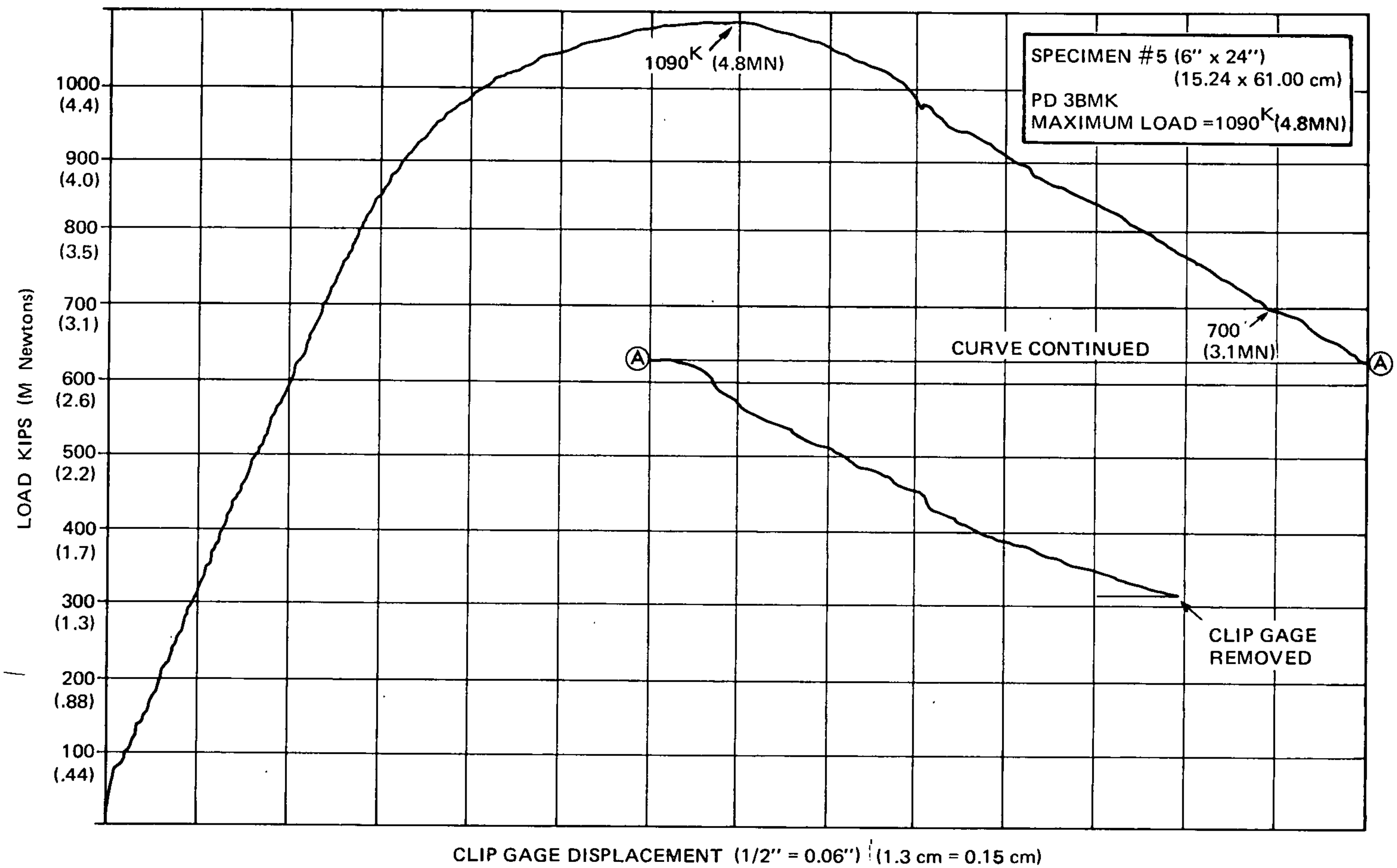


FIGURE 23 – LOAD-DISPLACEMENT CURVE FOR FRACTURE TOUGHNESS TEST OF SPECIMEN PD-3BMK

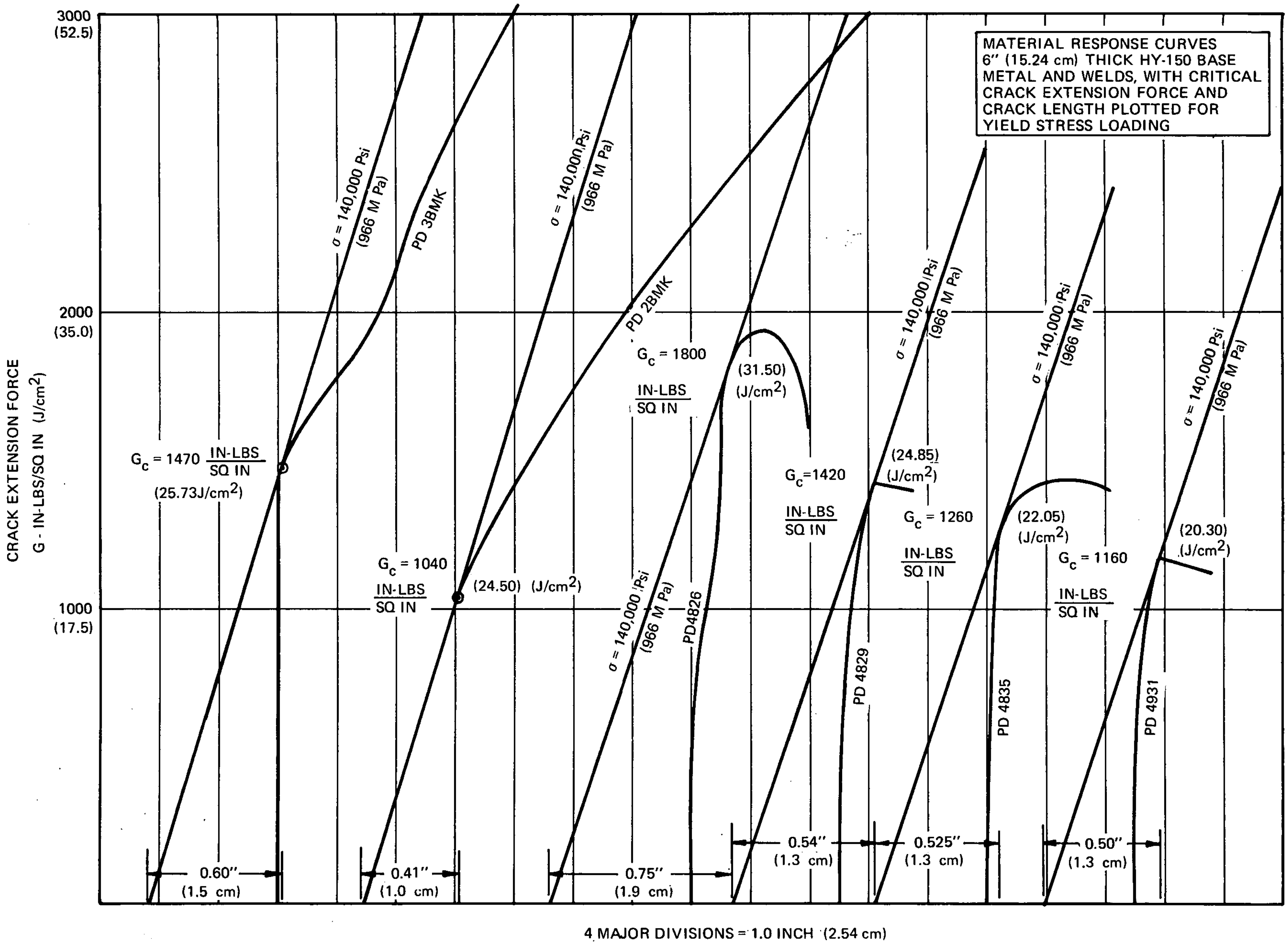


FIG 24 MATERIAL RESPONSE CURVES BASE METAL & WELDMENTS

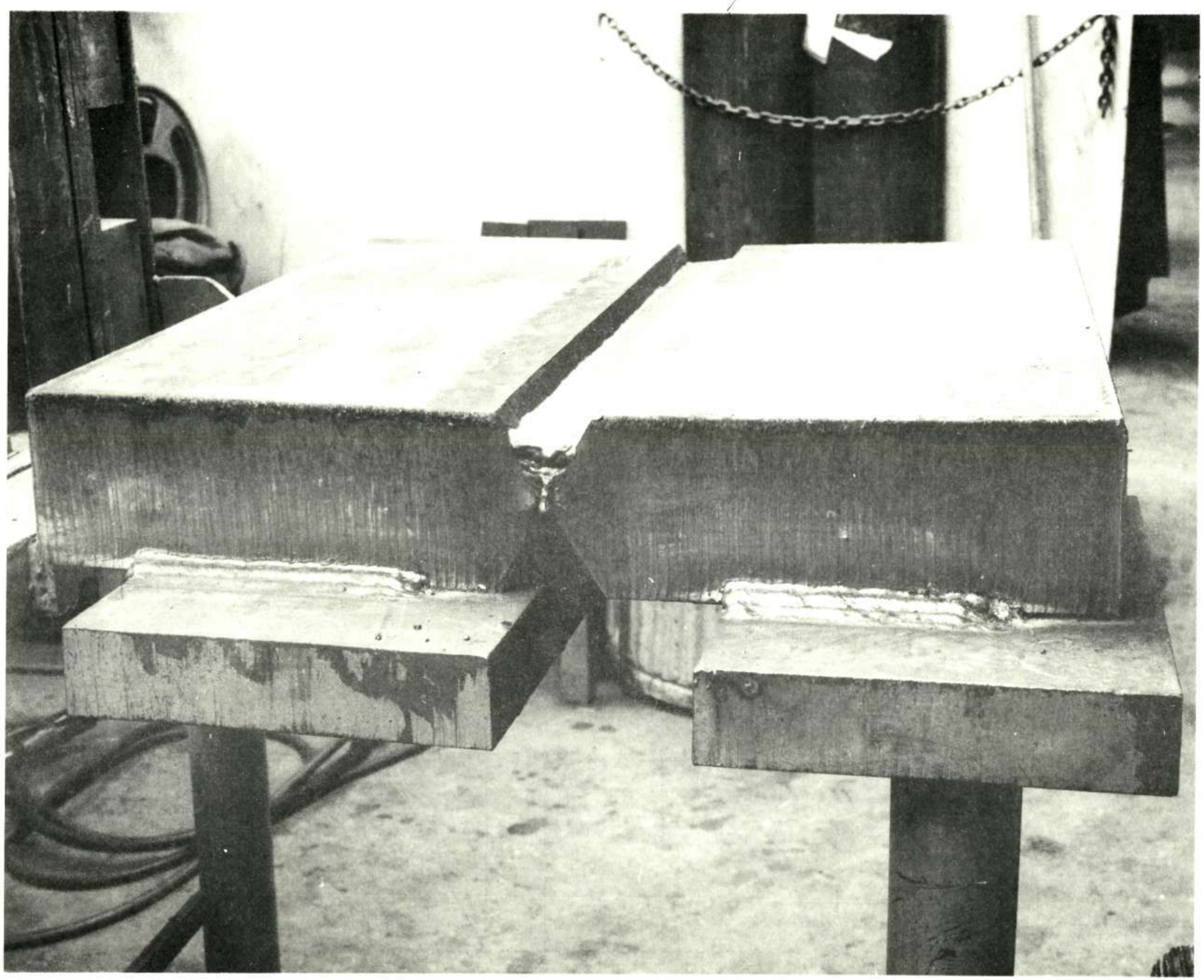
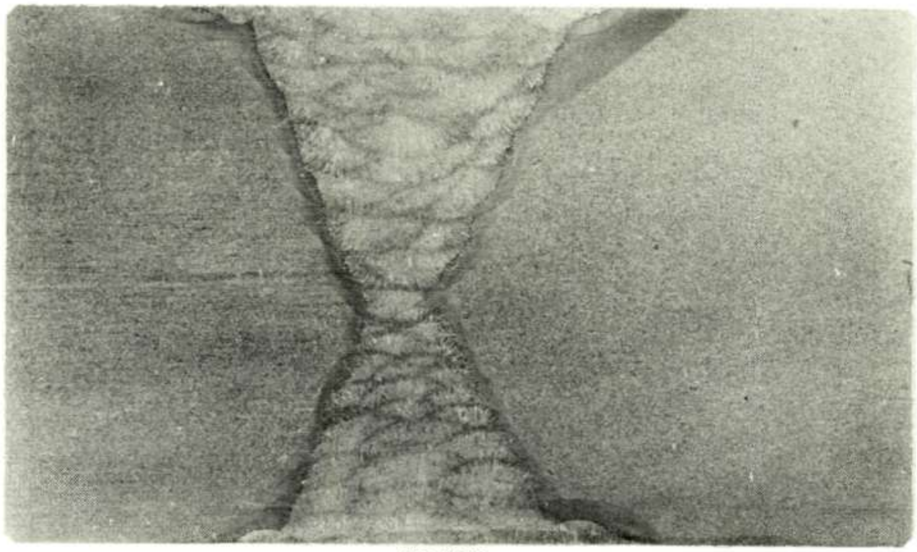
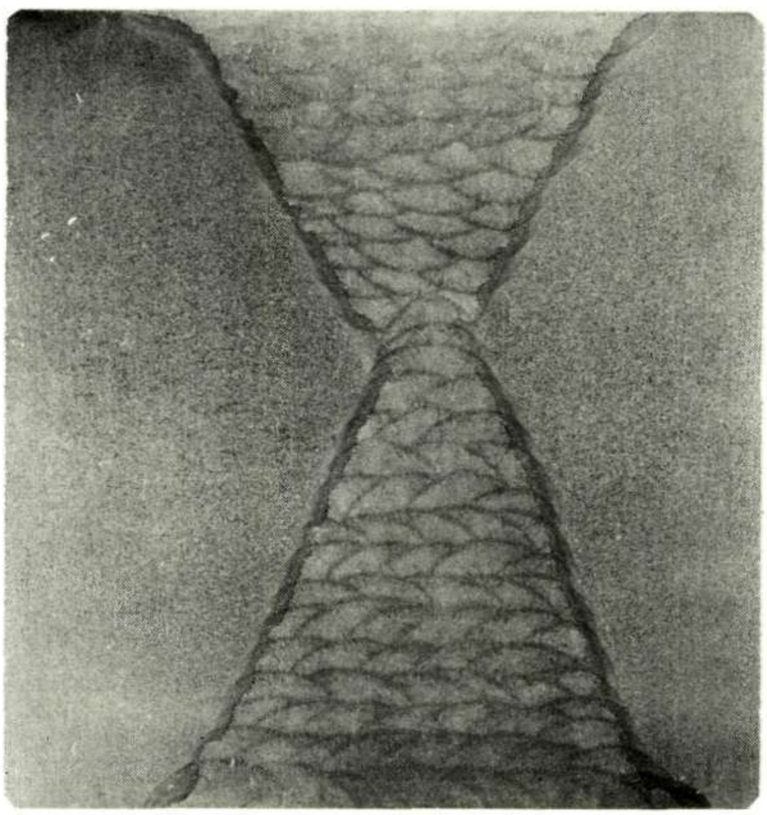


FIGURE 25 – PRELIMINARY WELD WIRE EVALUATION WELDMENT PD 4837 PARTIALLY COMPLETED AND EDGE FILLET WELDED FOR HIGH RESTRAINT

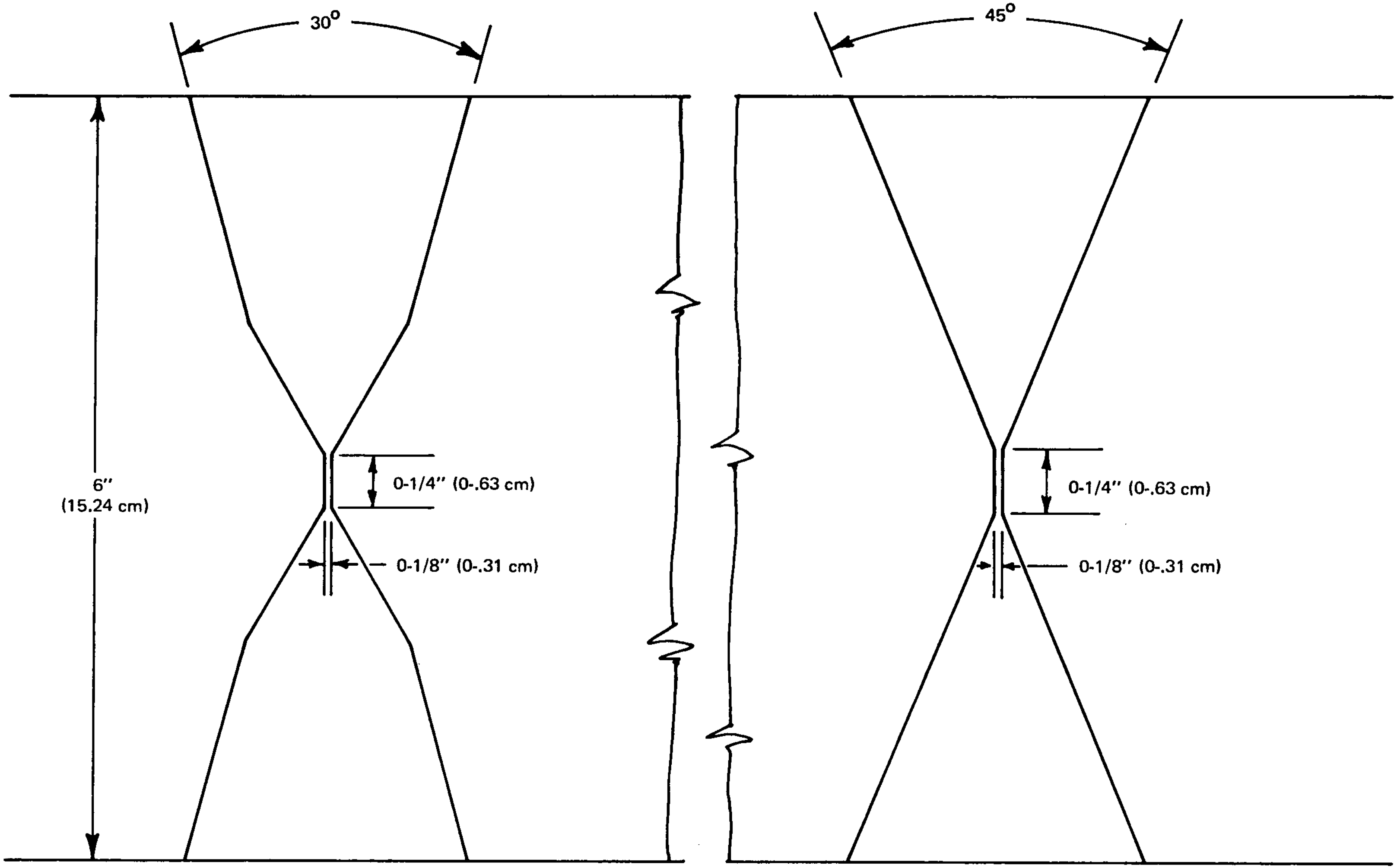


2% NITAL PD 4836 1.0X



2% NITAL PD 4837 1.4X

FIGURE 26 – PHOTO-MACROGRAPHS OF PRELIMINARY WELD WIRE EVALUATION TEST WELDMENTS PD 4836 AND PD-4837



ORIGINALLY PROPOSED

SELECTED FOR USE

FIGURE 27 - COMPARISON OF PROPOSED AND SELECTED TASK III AND IV WELD JOINT DESIGNS

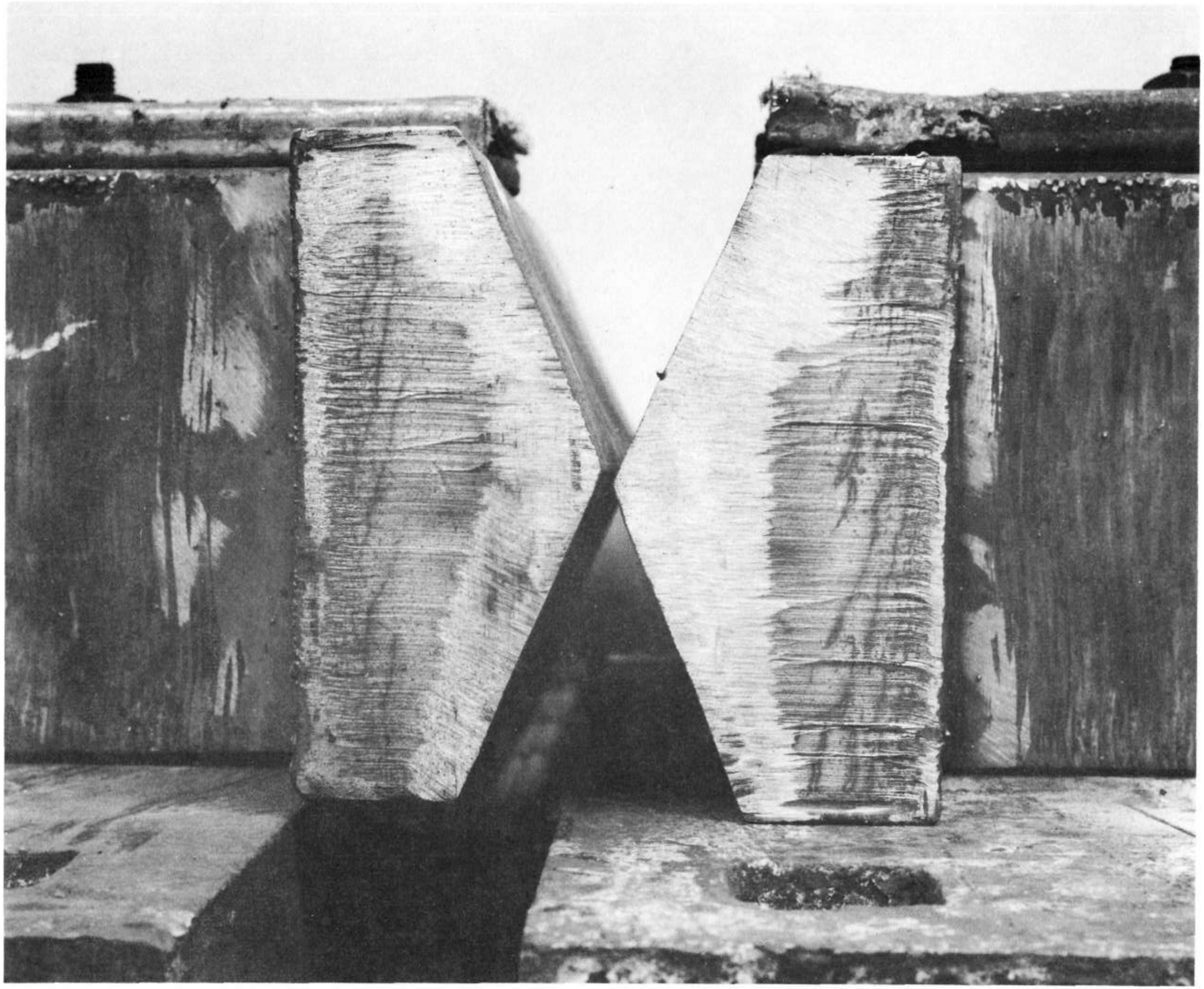


FIG 28 – WELD MISMATCH DETAILS, WELDMENT PD-4826

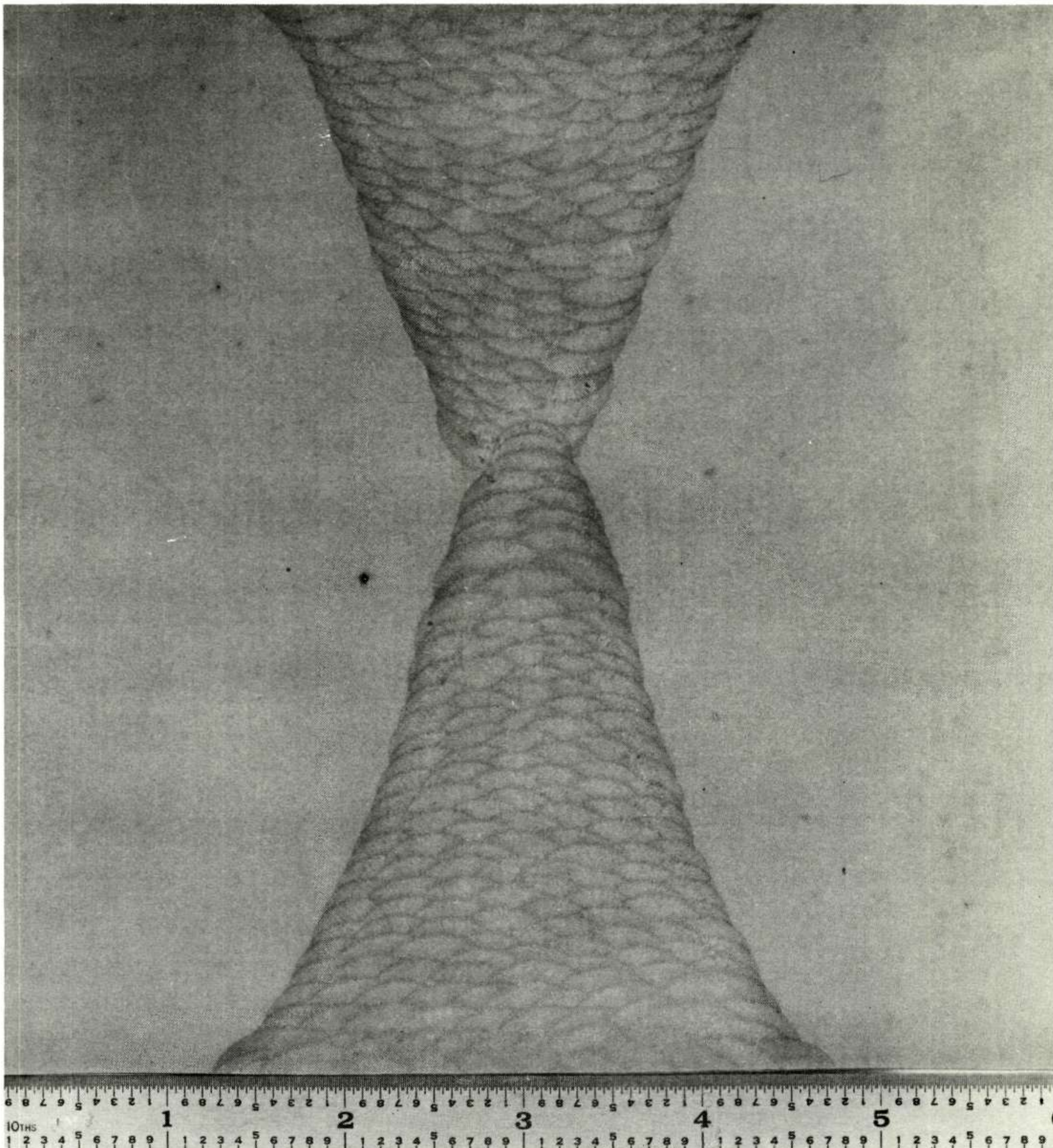
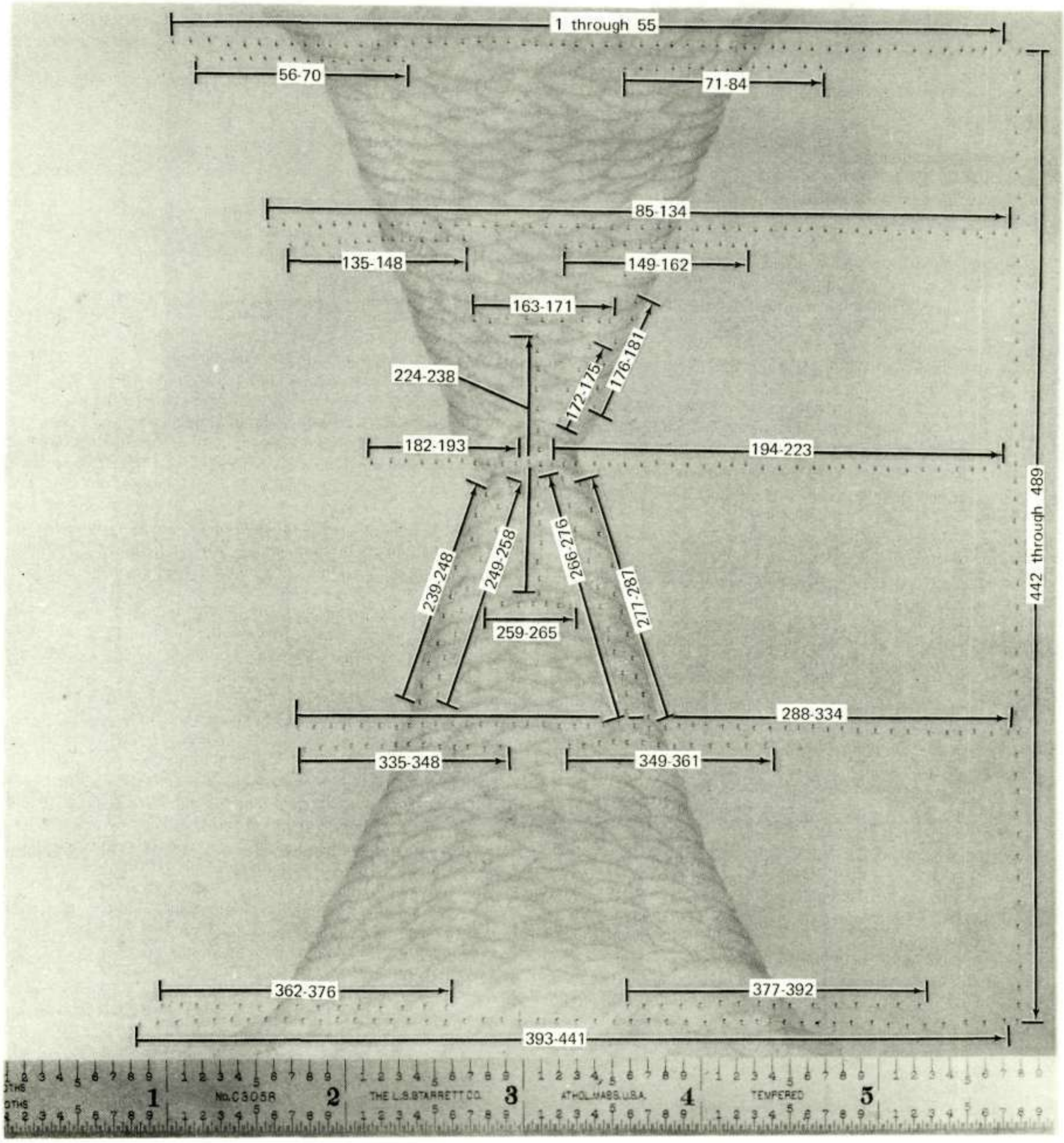
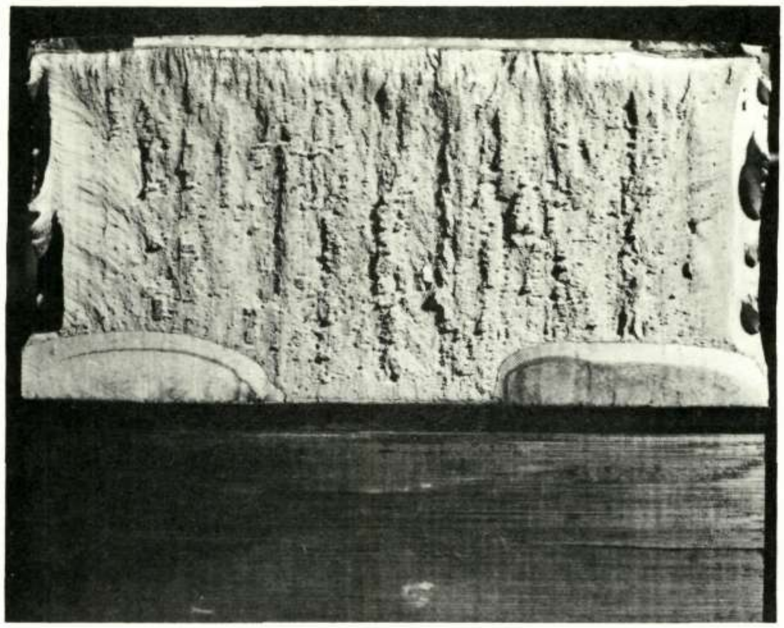


FIGURE 29 – MACROSECTION THROUGH WELDMENT PD-4827



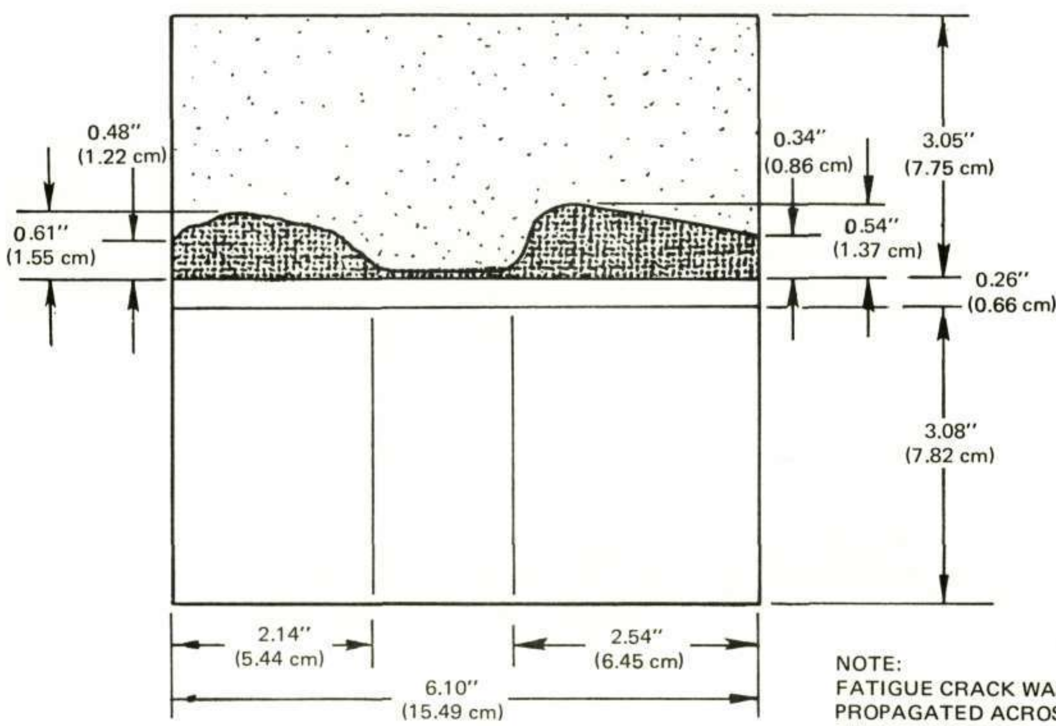
2% NITAL

FIGURE 30 R_C HARDNESS TRAVERSE PATTERN. WELDMENT PD-4827



PD-4826

PHOTO CREDIT:
LEHIGH UNIVERSITY



NOTE:
FATIGUE CRACK WAS PROPAGATED ACROSS ENTIRE WIDTH OF THE NOTCH.

FIGURE 31 – SPECIMEN PD-4826 FRACTURE SURFACE AND PRECRACK AREA DETAILS

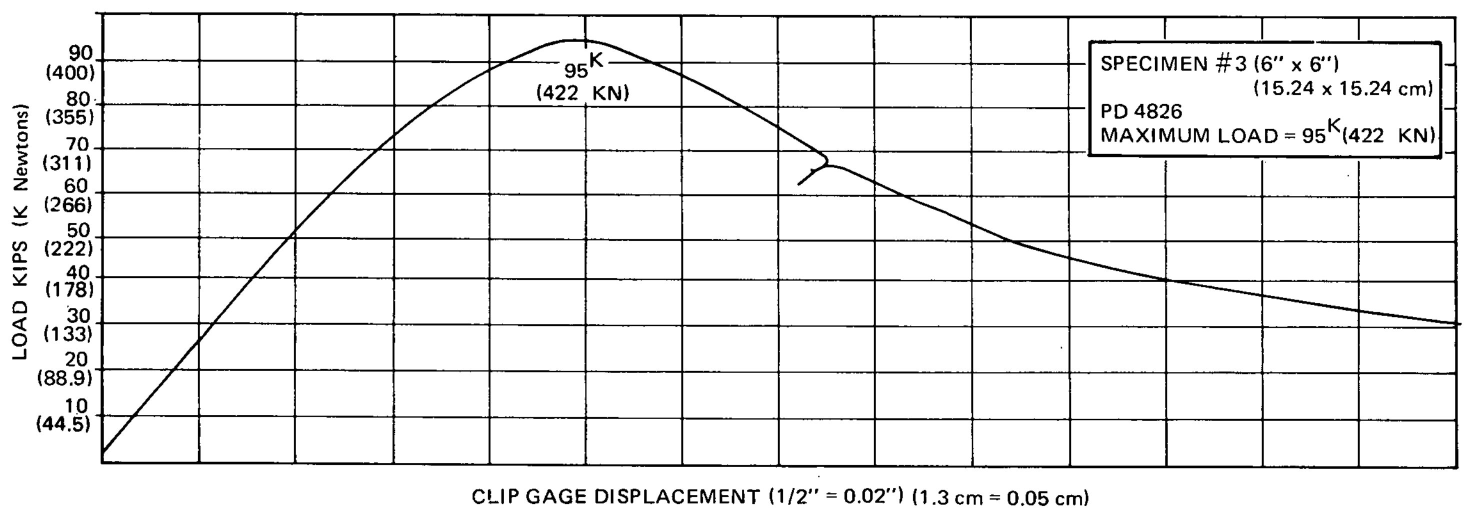
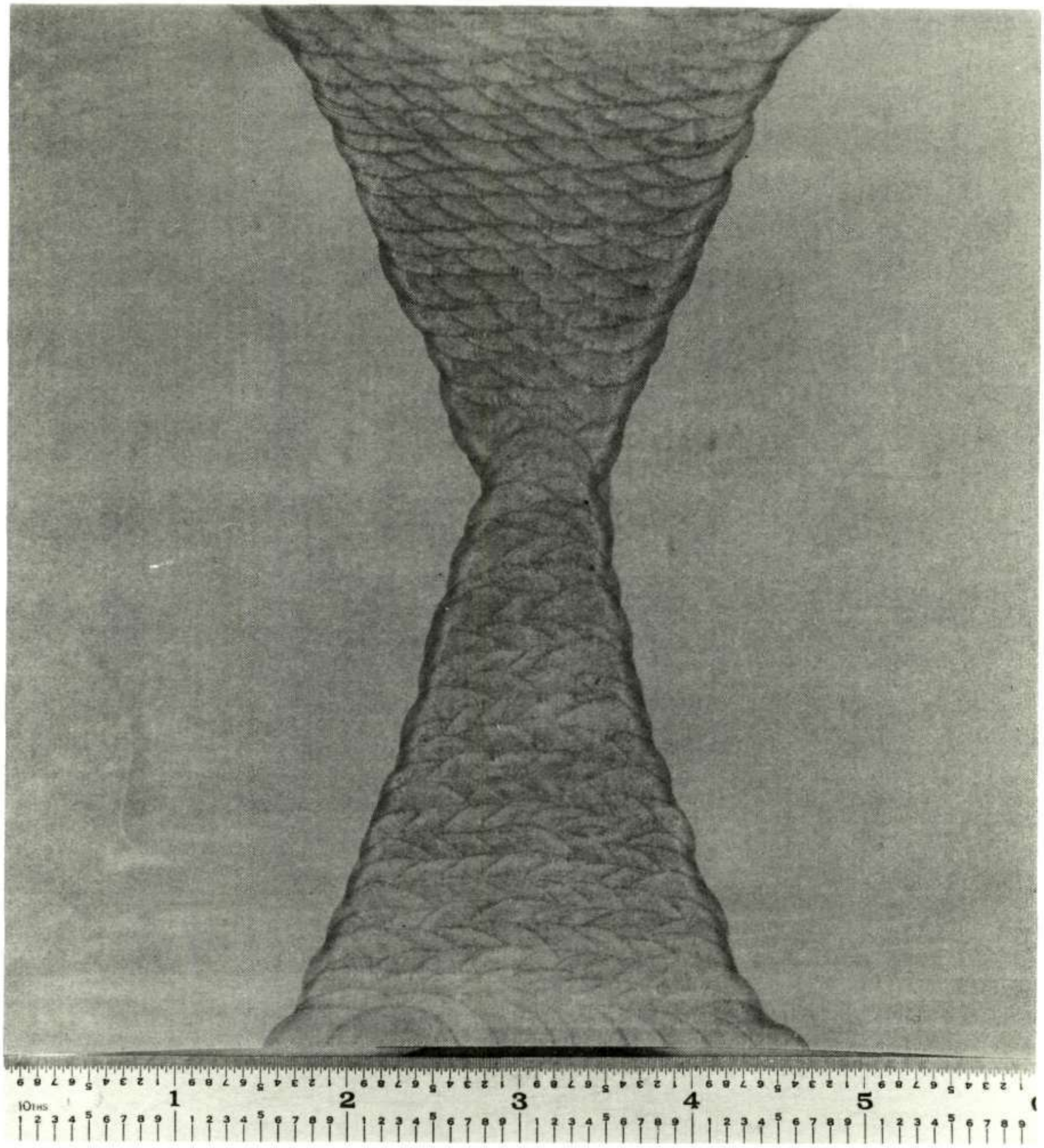


FIGURE 32 – LOAD vs. DISPLACEMENT RECORD, FRACTURE TOUGHNESS BEND SPECIMEN PD-4826.



2% NITAL

MAG: IX

FIGURE 33 – MACROSECTION THROUGH WELDMENT PD-4831

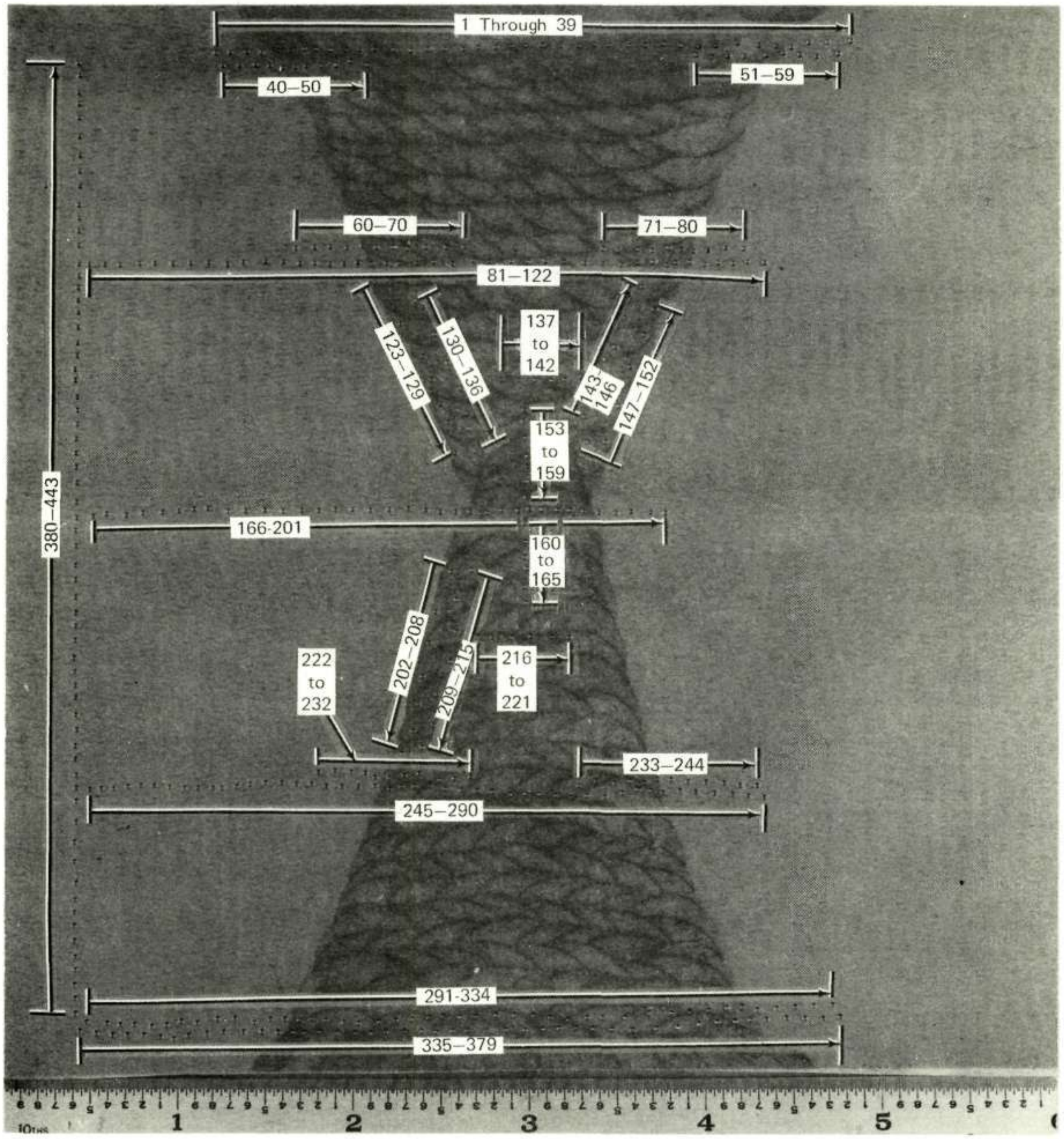
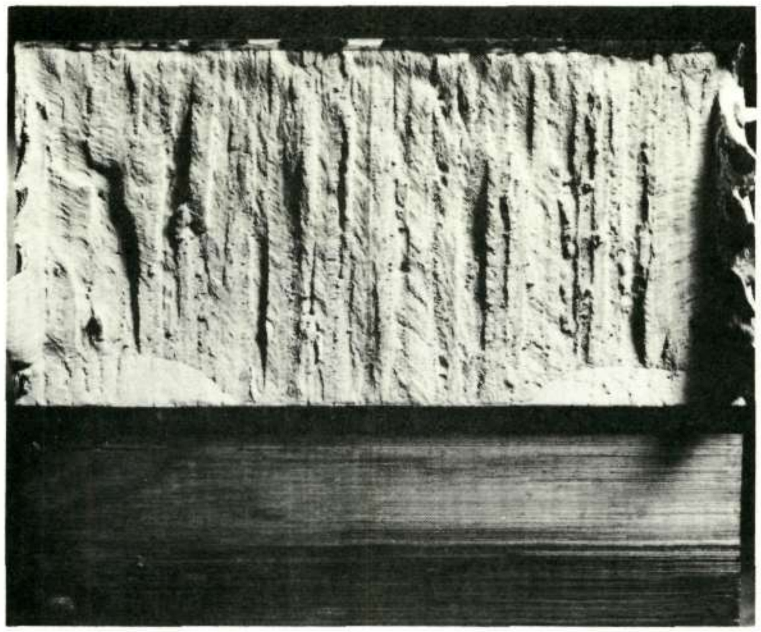
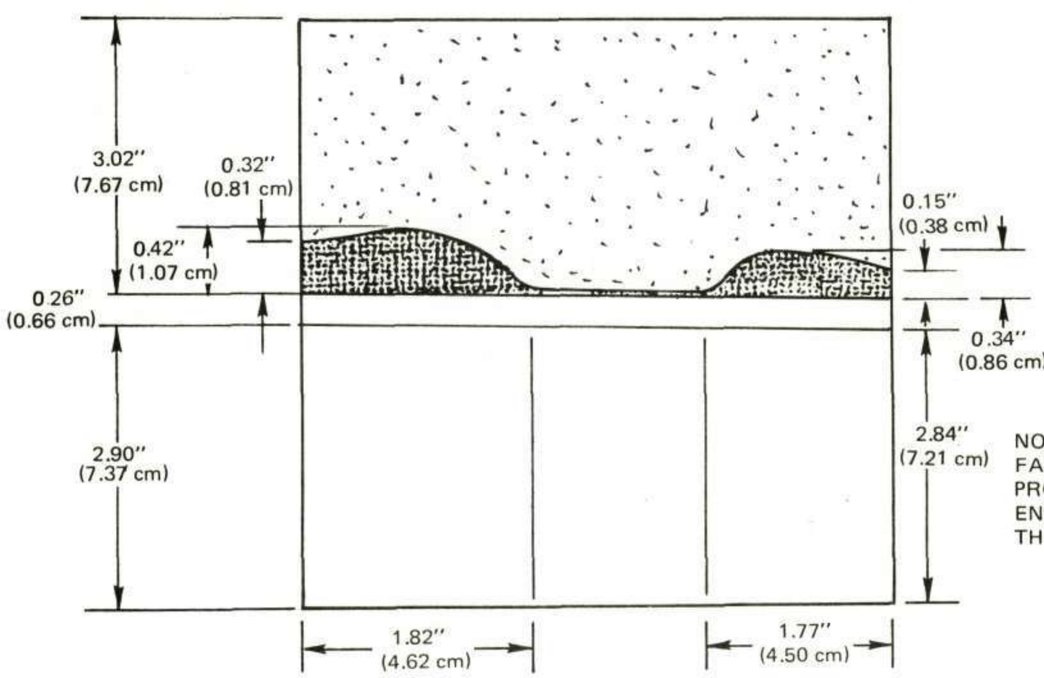


FIGURE 34 – R_C HARNESS TRAVERSE PATTERN, WELDMENT PD-4831



PD-4931

PHOTO CREDIT:
LEHIGH UNIVERSITY



NOTE:
FATIGUE CRACK WAS PROPOGATED ACROSS ENTIRE WIDTH OF THE NOTCH.

FIGURE 35 – SPECIMEN PD-4931 FRACTURE SURFACE AND PRECRACK AREA DETAILS

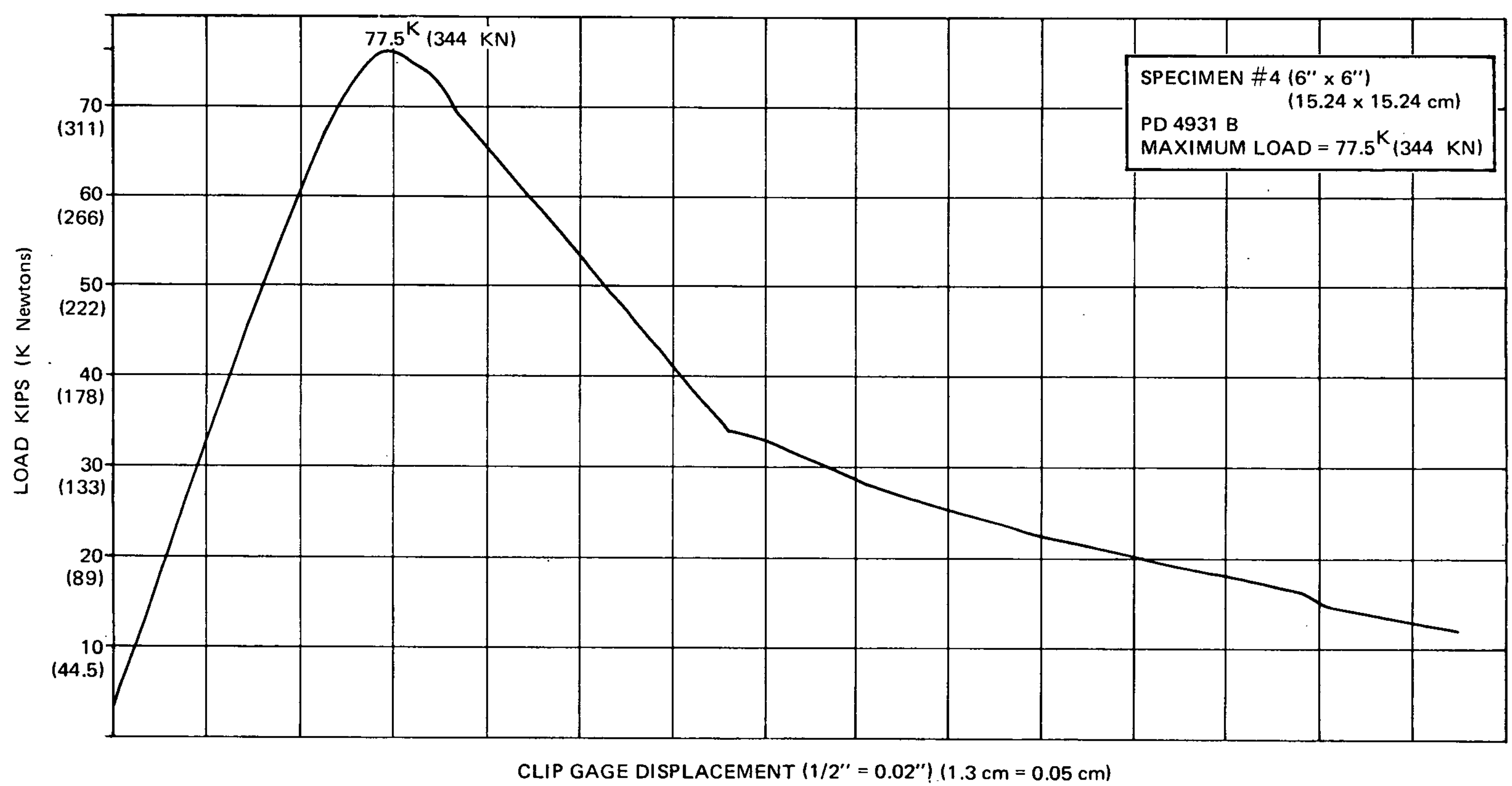
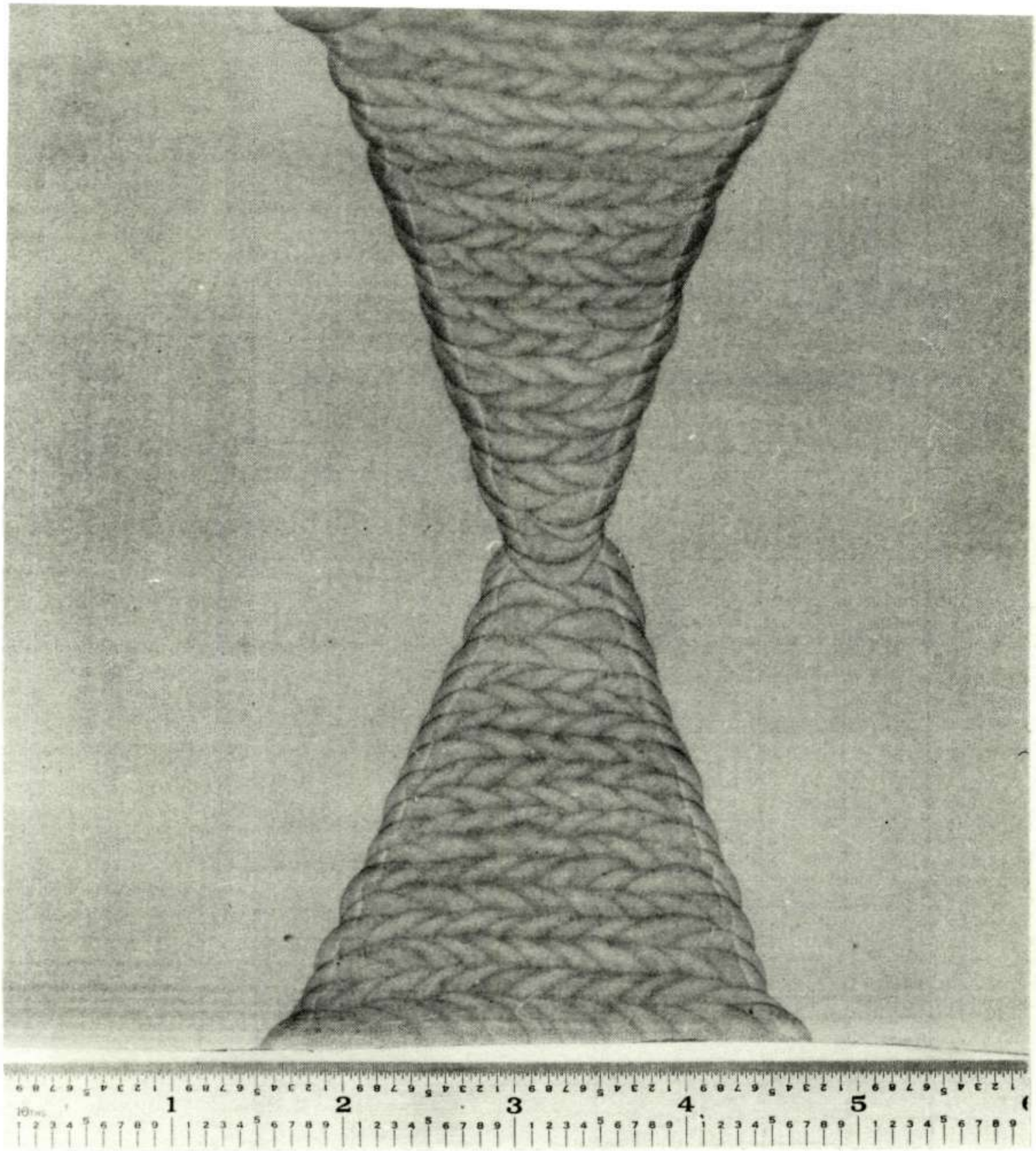


FIGURE 36 – LOAD vs. DISPLACEMENT RECORD, FRACTURE TOUGHNESS BEND SPECIMEN PD-4931



2% NITAL

MAG: IX

FIGURE 37 - MACROSECTION THROUGH WELDMENT PD-4824

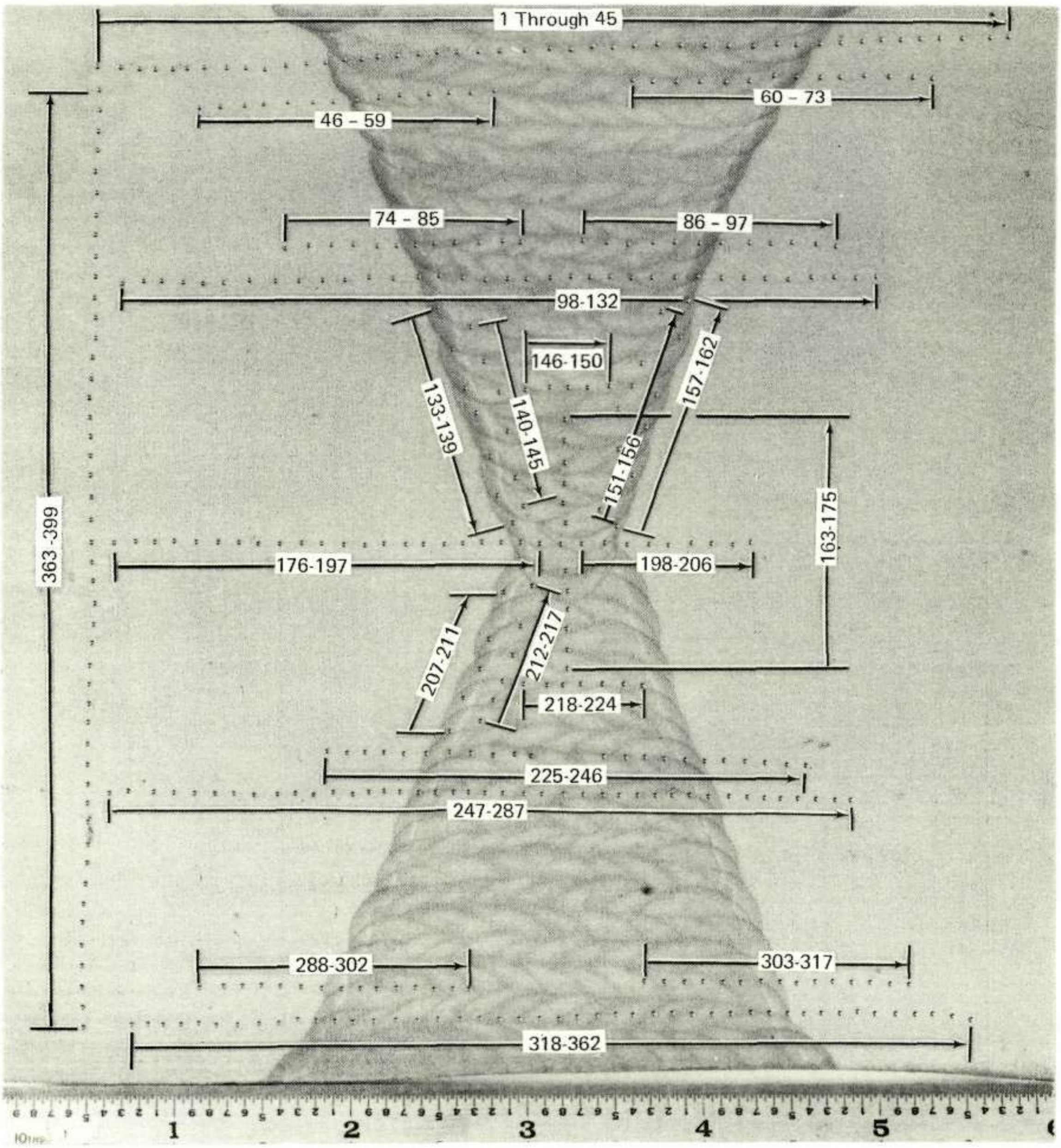
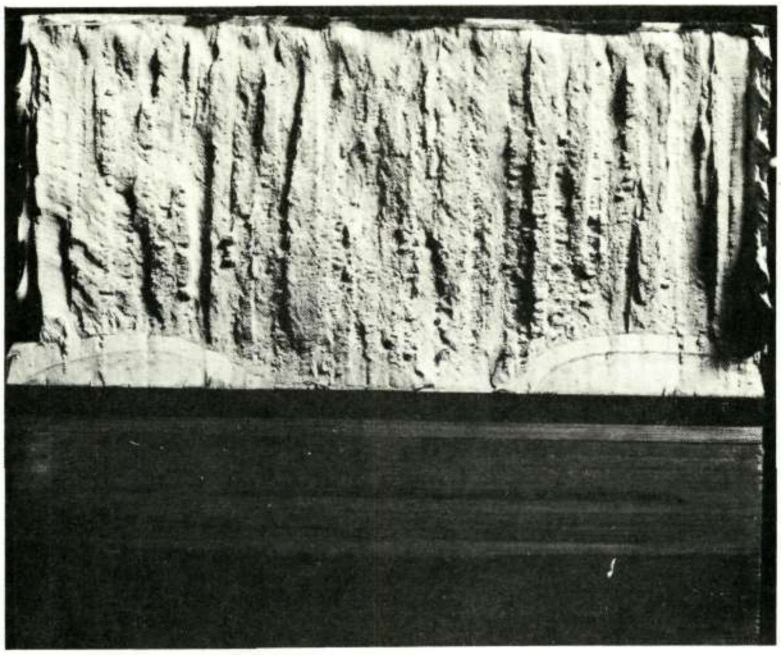


FIGURE 38 – R_c HARDNESS TRAVERSE PATTERN WELDMENT PD-4824.



PD-4829

PHOTO CREDIT:
LEHIGH UNIVERSITY

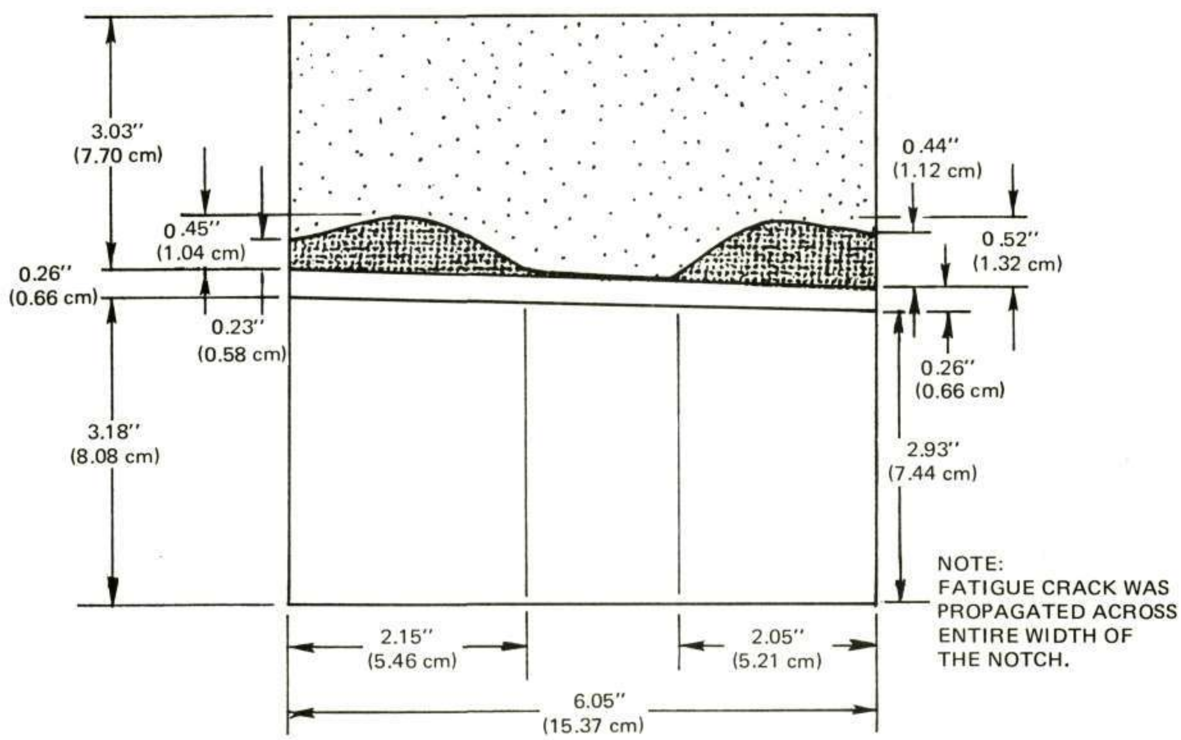


FIGURE 39 – SPECIMEN PD-4829 FRACTURE SURFACE AND PRECRACK AREA DETAILS

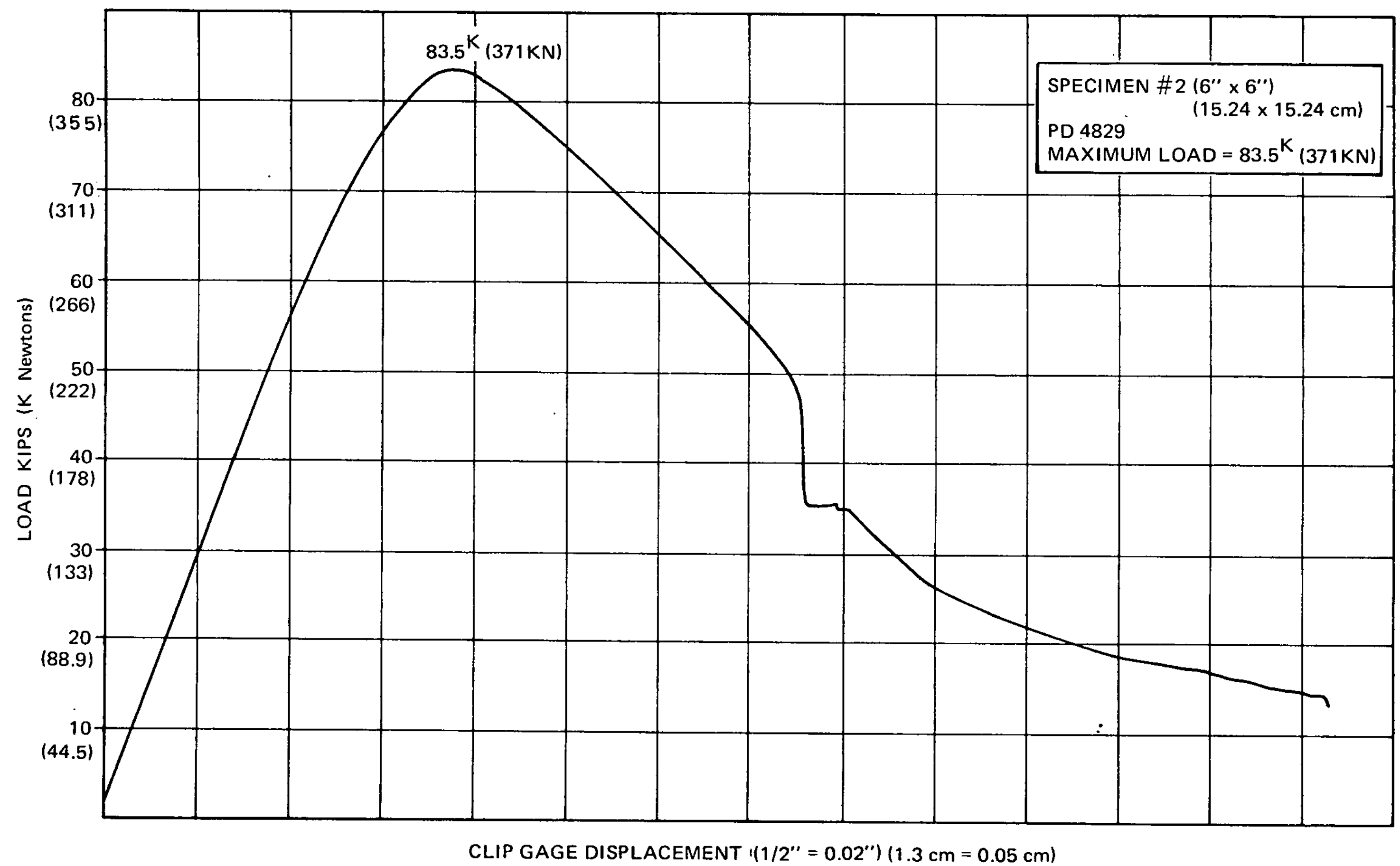
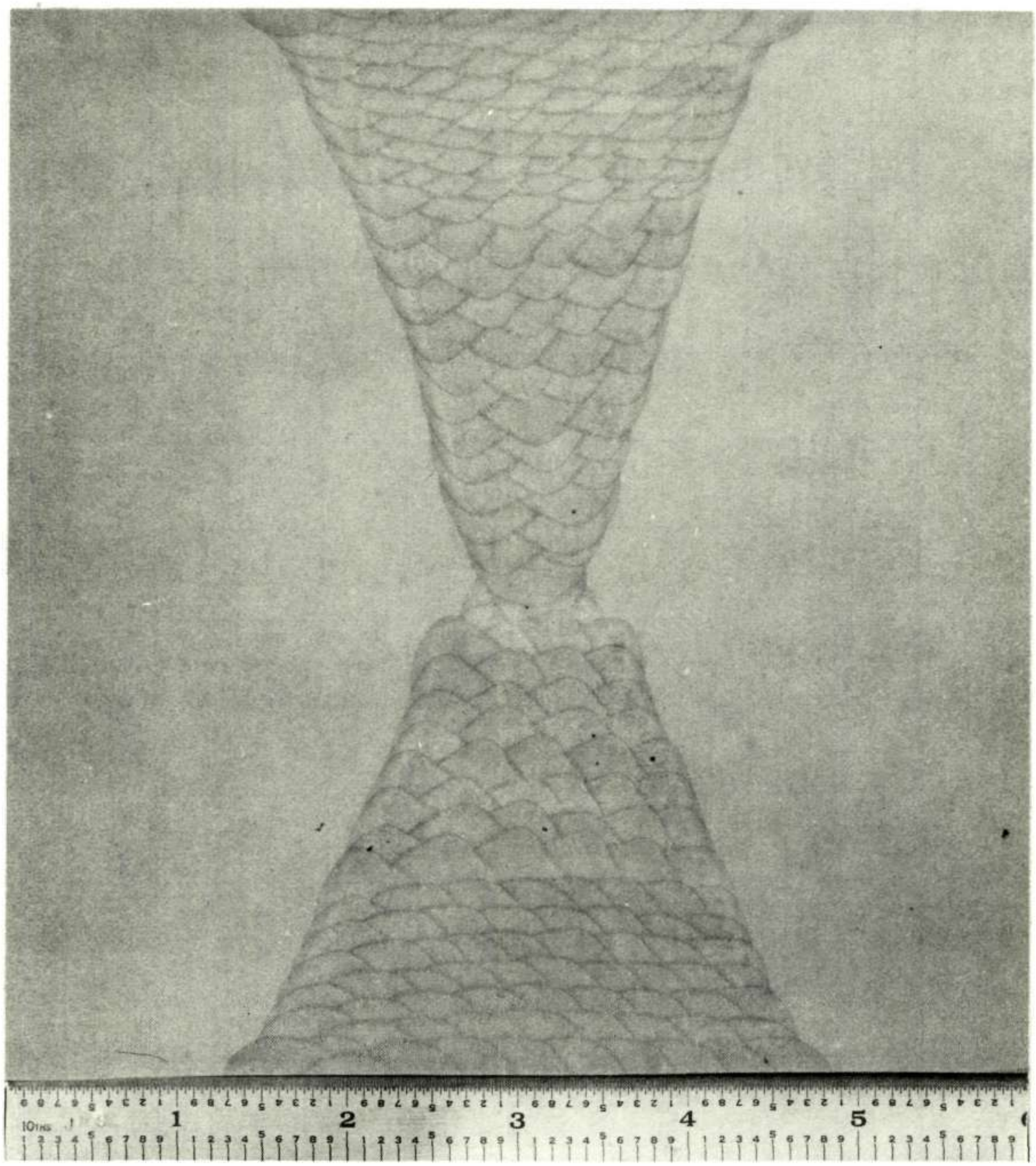


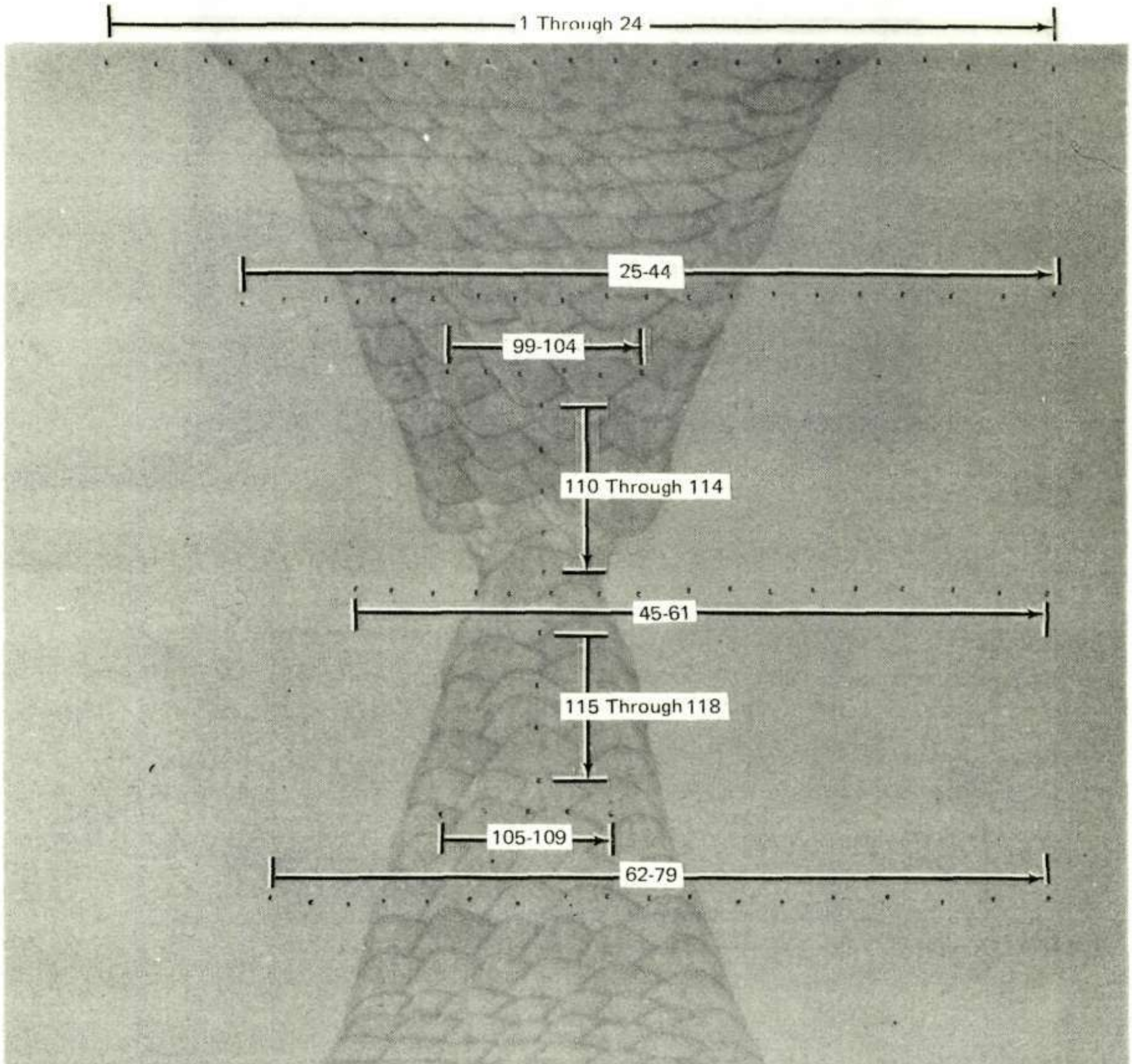
FIGURE 40 – LOAD vs. DISPLACEMENT RECORD, FRACTURE TOUGHNESS BEND SPECIMEN PD–4829



2% NITAL

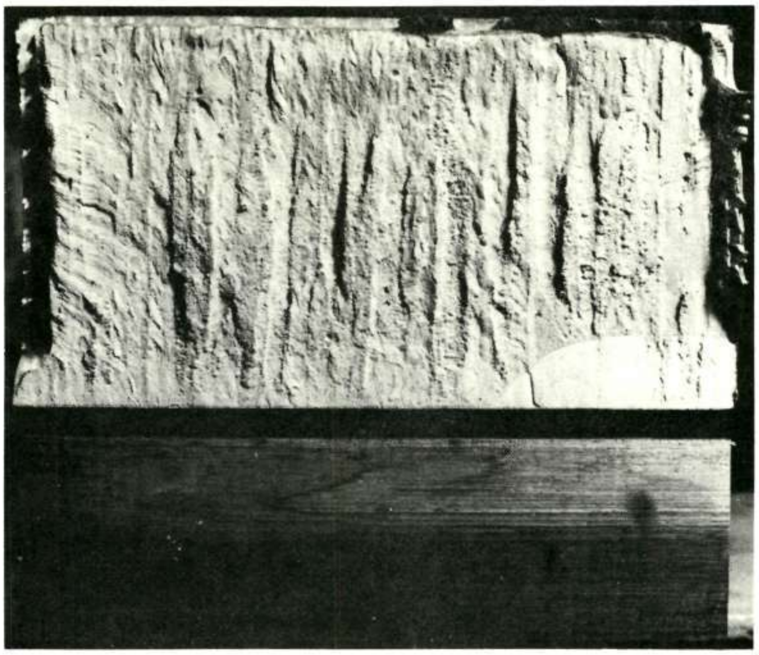
MAG: IX

FIGURE 41 – MACROSECTION THROUGH WELDMENT PD-4834



2% NITAL

FIGURE 42 – R_c HARDNESS TRAVERSE PATTERN, WELDMENT PD-4834



PD-4835

PHOTO CREDIT:
LEHIGH UNIVERSITY

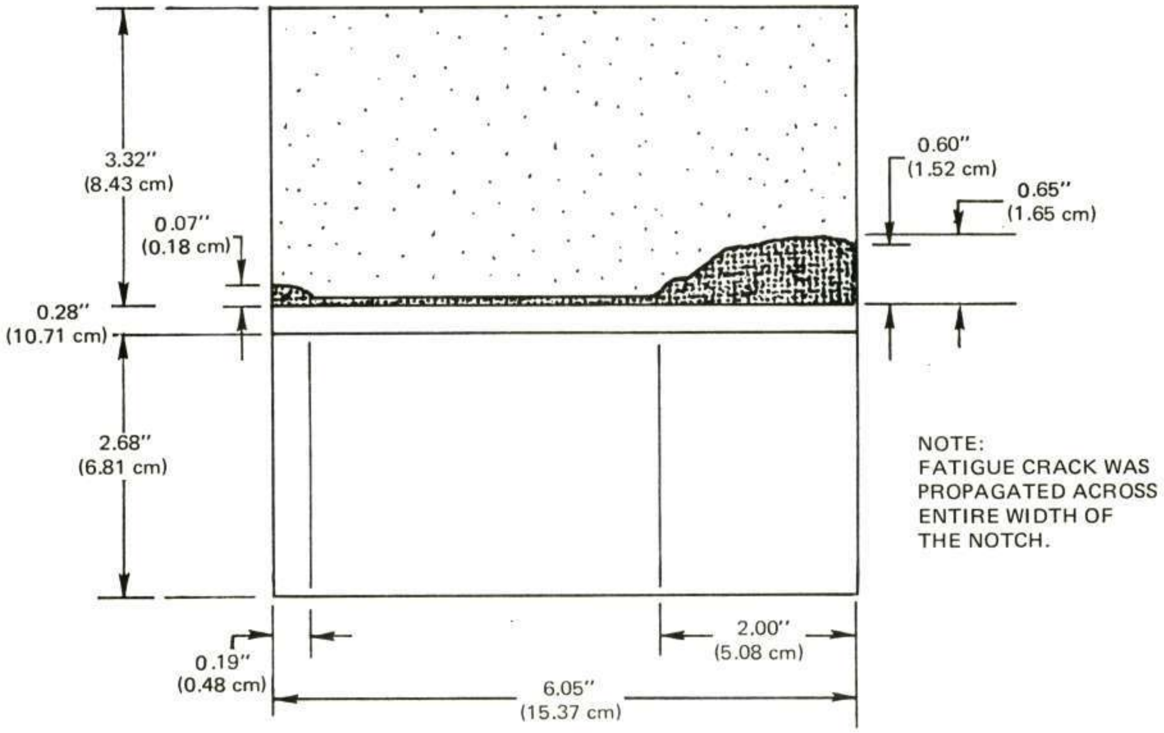


FIGURE 43 – SPECIMEN PD-4835 FRACTURE SURFACE AND PRECRACK AREA DETAILS

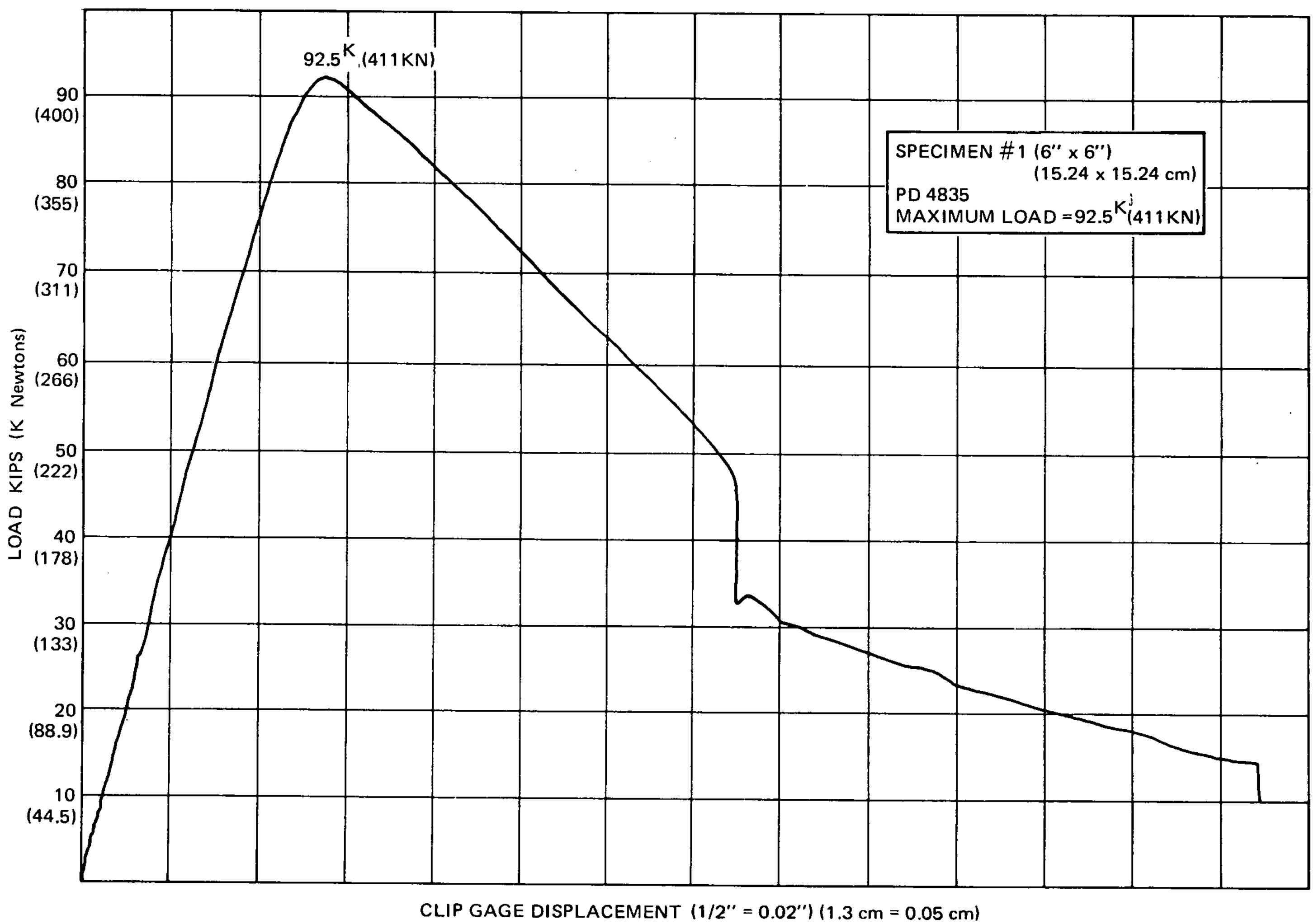


FIGURE 44 – LOAD vs. DISPLACEMENT RECORD, FRACTURE TOUGHNESS BEND SPECIMEN PD-4835.